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SULFUR OXIDE THROWAWAY SLUDGE EVALUATION PANEL (SOTSEP). VOLUME II: TECHNICAL DISCUSSION

Frank T. Princiotta

National Environmental Research Center
Research Triangle Park, North Carolina

April 1975

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The report gives results of an intermedia evaluation of the environmental and economic factors associated with disposal or utilization of sludge from non-regenerable flue gas desulfurization processes. The evaluation was conducted in the context of alternate sulfur oxide control techniques; existing and anticipated air, solid waste, and water standards; and other major influences on the potential generation of sludge, its disposal, and the magnitude of potential environmental problems associated with its disposal. This volume gives a comprehensive discussion of each study area and includes backup information and references for the Volume I Summary section.

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FOREWORD

This report by EPA's Sulfur Oxide Throwaway Sludge Evaluation Panel (SOTSEP) presents the results of an intermedia evaluation of the environmental and economic factors associated with disposal or utilization of sludge from nonregenerable flue gas desulfurization processes. The evaluation was conducted in the context of alternate sulfur oxide control techniques; existing and anticipated air, solid waste, and water standards; and other factors which might have a major influence on the potential generation of sludge, its disposal, and the magnitude of any potential environmental problems associated with its disposal.

The SOTSEP consisted of the following EPA members who participated in panel activities and co-authored the report:

Frank Princiotta (Chairman) - Office of Research and Development (ORD), National Environmental Research Center-Research Triangle Park (NERC-RTP), Control Systems Laboratory (CSL), Gas Cleaning and Metallurgical Processes Branch (GCMPB)

Arnold Goldberg - ORD, Air Pollution Control Division (APCD)

Julian Jones - ORD, NERC-RTP, CSL, GCMPB

William Schofield - ORD. NERC-RTP, CSL, Engineering Analysis Branch (EAB)

Richard Stern - ORD, NERC-RTP, CSL, GCMPB

Robert Walsh - Office of Air and Waste Management (OAWM), Emission Standards and Engineering Division (ESED), Office of Control Technology (OCT)

In addition to the above air pollution technology oriented members, the panel included water and solid waste pollution technology oriented associate members who actively participated in a consulting role and supplied inputs for the report:

Alden Christianson - ORD, NERC-Corvallis, Thermal Pollution Research Programs (TPRP)

Robert Dean - ORD, NERC-Cincinnati, Advanced Waste Treatment Research Laboratory (AWTRL), Ultimate Disposal Research Program (UDRP)

Ronald Hill - ORD, NERC-Cincinnati, AWTRL, Mine Drainage Pollution Control Activities (MDPCA)

Jack Keeley - ORD, NERC-Corvallis, Robert S. Kerr Environmental Research Laboratory, Ground Water Research (GWR)

Norbert Schomaker - ORD, NERC-Cincinnati, Solid and Hazardous Waste Research Laboratory (SHWRL), Disposal Technology Branch (DTB)

The results of the SOTSEP activity are presented in two separate volumes each covering the following general categories:

Definition of the problem - status of alternative sulfur oxide control technology, potential demand for lime/limestone scrubbing, quantification of the problem and comparison with analogous environmental problems, impact of SO_x scrubber sludge relative to current and proposed regulation/enforcement, and nature of the material.

Approaches to disposing of or utilizing scrubber sludge materials - commercial utilization, current and planned industry disposal, disposal by ponding, disposal by landfill, other disposal, and current EPA R&D programs.

Alternative sulfur by-products - technologies for production, economic and marketing considerations for elemental sulfur, sulfuric acid, gypsum, sodium sulfate, ammonium sulfate, and liquid SO_2, environmental considerations, and economic and environmental comparison with scrubber sludge.

Volume I, the Executive Summary, presents the panel findings and technical recommendations, followed by a Technical Discussion Summary which provides further details in each specific category of study.

Volume II, the Technical Discussion, provides a comprehensive discussion of each specific area of study and supplies back-up information and references for the Volume I Technical Discussion Summary.

Because of time constraints, SOTSEP activities were streamlined by working in accordance with the following groundrules:

1. The scope of the activities focused primarily on SO_x and particulate control for coal-burning power plant emissions. The flue gas desulfurization process was assumed to operate in a closed-loop with no direct discharge; liquor leaves the system only by evaporative losses in the scrubber and by inclusion with the sludge.

2. The study assumed that there would be no major deviations from either the Clean Air Amendments of 1970 or EPA's present implementation policies, through 1980.

3. Readily available information was utilized to the maximum possible extent.

4. Current CSL contractors were utilized to the maximum possible extent.

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Appreciation is acknowledged for the timely and responsive assistance of the following:

Radian Corporation which accumulated and evaluated a major portion of information, provided an early draft version of the Technical Discussion, and assisted in preparation of the final version of the report.

Aerospace Corporation which supplied scrubber sludge utilization information and chemical and physical property data, and assisted in review of the Executive Summary.

CSL secretaries Carolyn Fowler, Charlotte Bercegeay, Virginia Purefoy, Linda DeVinney, Gloria Rigsbee, Lynn Pendergraft, and Theresa Butts.

METRIC CONVERSION FACTORS

In compliance with EPA policy, metric units have been used extensively in this report (followed by British units in parentheses). However, in some cases, British units have been used for ease of comprehension. For these cases, the following conversion table is provided:

British	Metric
1 Btu	252 calories
1 Btu	2.93×10^{-4} kilowatt-hours
5/9 ($^{\circ}$F-32)	$^{\circ}$C
1 ft	0.3048 meter
1 ft^2	0.0929 $meters^2$
1 ft^3	0.0283 $meters^3$
1 yd	0.9144 meters
1 yd^2	0.8361 $meters^2$
1 yd^3	0.7646 $meters^3$
1 mile	1.609 kilometers
1 $mile^2$	2.59 $kilometers^2$
1 acre	4047 $meters^2$
1 pound	0.4536 kilograms
1 ton (short)	0.9072 metric tons

I. DEFINITION OF THE PROBLEM

A. AVAILABILITY OF ALTERNATIVE SO_x CONTROL TECHNOLOGY

1.0 Introduction

Recent air quality legislation such as the Federal Air Quality Act of 1967 and the Clean Air Amendments of 1970 have had, and will continue to have, a decided impact on the demand for sulfur oxide control equipment and new sources of clean fuels for the electric utility industry. Legislation has been promulgated at the federal, state, and local levels to control emissions of air pollutants from mobile sources and significant stationary sources. Emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulates are of particular concern to fossil fuel-fired power plants, since power plants are the largest stationary sources, both individually and collectively, of all three pollutants. This section deals specifically with SO_x emissions, which are about 97 percent sulfur dioxide (SO_2).

Barring any relaxation of the current regulations, fossil-fueled generating stations, for which construction was initiated after about January 1971, will have to bring stack gas emissions of SO_2, NO_x, and particulates within prescribed New Source Performance Standards (NSPS). Furthermore, all states have established regulations that require control of SO_2 and particulates (and in some cases NO_x) from existing sources. The principal target date of state programs is July 1975, when primary national ambient air quality standards (NAAQS) are to be achieved. Secondary NAAQS are more stringent than primary standards in the case of particulates and SO_2 and, therefore, require more effective control of source emissions. Secondary NAAQS must be attained in a reasonable time. Table I-1 lists EPA NSPS for SO_2 emissions from fossil fuel-fired steam generators; Table I-2 lists NAAQS for SO_2. Table I-3 presents typical state/local limits on SO_2 emissions from State Implementation Plans (SIP) for meeting NAAQS.

The problem of reducing SO_2 emissions is heightened by the needs of the Nation's utility industry to meet the spiraling demand for electric power generation. According to a scenario developed by the U. S. Department of the Interior (USDI) in December 1972, the growth in net energy consumption is reflected by the growth in the Nation's electric generation sector from 1.61 billion megawatt-hours (Mwh) in 1971 to 2.13 and 3.00 billion Mwh in 1975 and 1980, respectively (Ref. 1). Predicted trends among these three energy types, fossil fuel, nuclear, and hydropower, are illustrated in Table I-4. Although the percentage of the total energy generation burden supported by fossil fuels will begin to decrease as nuclear power becomes available, the total installed generating capacity of fossil-fueled boilers is expected to increase from 303 to 445 thousand Mw by 1980.

This section addresses the problem of generating this additional 140 thousand Mw of electricity, as well as that from plants already on stream, in a manner consistent with current federal, state, and local air quality control regulations for SO_2. To accomplish this, a number of alternatives are available.

One of these, of course, is the direct burning of naturally available clean fossil fuels; i.e., low-sulfur coal and oil, and natural gas. However, it is recognized that clean fuel supplies are not available in quantities needed for present

Table I-1. NEW SOURCE PERFORMANCE STANDARDS (NSPS) FOR FOSSIL FUEL-FIRED STEAM GENERATORS > 250 X 10^6 Btu/hr[a]

Fuel Type	Maximum Allowable Emissions for SO_2 (grams/1000 Kg-calories)
Coal	2.2
Oil	1.4[b]

[a] Reference 1

[b] Not to be exceeded more than once a year.

Table I-2. NATIONAL AMBIENT AIR QUALITY STANDARDS (NAAQS) FOR SO_2

Averaging Time	Primary		Secondary	
	$\mu g/m^3$	ppm	$\mu g/m^3$	ppm
Annual	80	0.03	60	0.02
24 Hour[a]	365	0.14	260	0.1
3 Hour			1300	0.5

[a] Not to be exceeded more than once a year.

Table I-3. TYPICAL STATE IMPLEMENTATION PLANS FOR EXISTING BOILERS IN STATES USING COAL[a]

State	Regulation (or Equivalent) ($\text{lb } SO_2/10^6$ Btu Fired)
Ohio	1.0[b]
Tennessee	1.5[b,c,d]
Kentucky	1.2[e,f]
Alabama	1.2[c,f]
Michigan	1.0[d,f]
Pennsylvania	0.6 to 1.0 (depending on size)[f]
West Virginia	2.7[f]
Illinois	1.8[f]

[a] As of June 1973

[b] Effective July 1, 1975

[c] Under revision

[d] Regulations in different terms

[e] Effective July 1, 1977

[f] Less stringent in some areas of the state

Table I-4. INSTALLED GENERATING CAPACITY AND NET GENERATION IN THE ELECTRIC UTILITY INDUSTRY (1971 Actual and Projected to 1980)[a]

Period: Type of Plant	Installed Generating Capacity Mw	Load Factor	Net Generation, Billion Kwh	% of Total
1971:				
Fossil Fuel Burning Plants	302,810	0.50	1,310	81.2
Nuclear Plants	8,687	0.50	38	2.3
Hydropower Plants	55,898	0.55	266	16.5
TOTAL	367,395	0.51	1,614	100.0
1975:				
Fossil Fuel Burning Plants	350,000	0.50	1,540	72.3
Nuclear Plants	50,000	0.55	240	11.3
Hydropower Plants	80,000	0.50	350	16.4
TOTAL	480,000	0.51	2,130	100.0
1980:				
Fossil Fuel Burning Plants	445,000	0.50	1,950	65.0
Nuclear Plants	120,000	0.60	630	21.0
Hydropower Plants	95,000	0.50	420	14.0
TOTAL	660,000	0.52	3,000	100.0

[a] USDI (Reference 1)

and projected needs. In light of the clean fuel deficit, a number of potential approaches to utilizing high sulfur fuels as energy sources are being investigated. The technologies under consideration are as follows:

1. Physical coal cleaning
2. Chemical coal cleaning
3. Desulfurization of oil
4. Flue gas cleaning
5. Fluidized bed combustion
6. Coal gasification (high heat value (HV) gas)
7. Coal gasification (low HV gas)
8. Coal liquefaction

These technologies for utilization of high sulfur fuels are discussed in Section 3.0.

2.0 Impact of Fuel Switching and Supplementary Control Strategy on Supply

In light of the difficulty new generating stations are experiencing in obtaining long-term supply contracts from coal companies, many new plants are being designed for multi-fuel operation. That is, they are equipped to fire more than one fuel type--usually coal and oil or gas and oil. If the supply of a utility's major fuel type is curtailed temporarily, spot reserves of the secondary fuel may be tapped to fill the void.

Two EPA-initiated plans may provide some existing power plants with relief from extremely stringent SO_2 emission restrictions. These are: (1) the Clean Fuels Policy enunciated by former EPA Administrator Ruckelshaus in a letter to all state governors; and (2) the use of supplementary control systems as an interim measure until adequate constant control measures can be applied. It is emphasized that both approaches apply only to existing sources and would have no effect on federal emission standards for new steam generators.

The Clean Fuels Policy was developed in recognition of the low-sulfur fuels deficits. Evaluation of state SO_2 emission limitations indicates that in at least some areas greater restrictions are being imposed on existing sources than are necessary to meet primary NAAQS. Consequently, Mr. Ruckelshaus informed all state governors in December 1972, that they should review implementation plans and consider revisions with the aim of meeting only the health-oriented primary NAAQS by July 1975. To date there have been few state actions to relax SO_2 emissions from fuel burning sources. Nevertheless, several are under consideration. For example, the State of Ohio restricts SO_2 emissions from all power plants to the equivalent of coal containing 0.6 percent or lower sulfur content. This regulation was enacted even though many areas of Ohio do not require such stringent control to meet either primary or secondary NAAQS. As a result of current litigation, state officials have indicated that they intend to set compliance schedules and revise SO_2 emission limits where necessary such that NAAQS can be realized through a more realistic program.

Realization of the Clean Fuels Policy objectives will require information concerning air quality in the vicinity of power plants. Since much of this information is now lacking, judgments frequently cannot be made as to the degree of SO_2 control required to meet NAAQS. In addition, some states may not decide to initiate necessary changes in regulations. The Clean Air Act clearly allows states and local jurisdictions to establish air pollution control regulations which are more restrictive than necessary to meet federal standards (NAAQS and new source performance standards).

Application of supplementary control systems involves the use of measures such as temporary fuel switching (to low sulfur fuel) or decreasing boiler load to curtail the rate of emissions from a source when meteorological conditions conducive to high ground-level pollutant concentrations exist or are anticipated. This approach is considered a stopgap measure to attain and maintain national standards without unduly disrupting production of important products (particularly nonferrous metals) and electric power plants. It would serve in the interim until stack gas cleaning hardware has been designed, built, and installed or new sources of fuel have been developed.

It is unlikely, however, that supplementary control will have significant impact on the clean fuel supply/demand balance since the tentative EPA amendments prohibit its use for sources where other control options are available. This provision would preclude its use for oil-fired steam generators and for new steam generators of all types. Coal-fired electric generating plants may be permitted use of supplementary control only if not to do so would either delay attainment of the national standards or permanently curtail power production.

3.0 Technologies for Utilization of High Sulfur Fuel

Methods available or being developed to utilize high sulfur fuels for energy while complying with environmental regulations include a variety of techniques which vary widely from the standpoint of complexity and stage of development. The methods can be divided logically into the following eight classes or technologies which are discussed below:

1. Physical coal cleaning
2. Chemical coal cleaning
3. Desulfurization of oil
4. Flue gas cleaning
5. Fluidized bed combustion
6. Coal gasification (high HV gas)
7. Coal gasification (low HV gas)
8. Coal liquefaction

Comparative economics of these technologies are discussed in Section 4.0.

3.1 Physical Coal Cleaning

Since the late 1960's EPA has supported work to define the usefulness of available coal cleaning methods for removal of sulfur from coal. Such methods involve crushing coal to about 1 cm (3/8 inch) or less to liberate pyritic sulfur and passing it through equipment which separates the high density fraction where pyrite is concentrated. To date coals from over 300 mines have been tested. Fifteen to 20 percent of the coal supplies are capable of being cleaned to less than 1 percent total sulfur. The average reduction for all coals tested was 30 percent. For many, 50 percent reductions were possible. It is not possible to reduce sulfur in many coals to the very low levels required by some control regulations. However, physical coal cleaning is a low cost control technique utilizing readily available hardware which will be useful with cleanable coals, either alone or in combination with other methods such as flue gas cleaning.

3.2 Chemical Coal Cleaning

Chemical coal cleaning processes are designed to remove pyritic sulfur, organic sulfur, or both from the coal. Two processes appear to be worthy of note.

One process for the removal of pyritic sulfur from coal utilizes the reaction of ferric ion with the pyritic sulfur (Meyers Process developed by TRW). The system may obtain 95-100 percent removal of pyritic sulfur. To date effective removals have been obtained using coal up to 0.65 to 0.75 cm size. More effective (time-wise) removal is seen at the 149 micron (100 mesh) size. If extremely fine size coal is required, agglomeration after cleaning may also be required in the process.

The above process does not alter the nature of the coal. In addition, this process is scheduled to be in pilot operation during fiscal year 1974. An estimate for commercial utilization is premature at the point, but the application is a minimum of 5 to 6 years away.

3.3 Desulfurization of Oil

Several commercial processes are available for desulfurizing distillate crude and residuum to various levels of required sulfur content. The most desirable process in any situation is a function of the feedstock characteristics and sulfur level required in the end product.

Desulfurization processes basically involve reaction of the sulfur in the oil with hydrogen in a catalytic reactor usually at high temperatures and pressures. A major variation in the processes involves the fraction of the crude that is hydrodesulfurized: atmospheric gas oil distillate, atmospheric residuum, vacuum gas oil distillate, or vacuum residuum.

One approach offered by several companies is that of desulfurizing the vacuum gas oil and blending the desulfurized distillate with the high sulfur vacuum residuum. This type of operation is capable of producing a product of 1.0 to 2.5 percent sulfur (Ref. 2).

Hydrodesulfurization of the atmospheric residuum, which contains the vacuum distillate and vacuum residuum fractions, can yield a product of lower sulfur levels, 0.3-1.0 percent; however, to reach the very low sulfur levels of 0.3 percent and lower, the heavy vacuum residuum must be desulfurized (Ref. 2). Desulfurization of heavy residual oils requires more complex processing to cope with the fouling and coking tendencies of the difficult feeds.

One process that deals with this problem is Exxon Research and Engineering Company's Flexicoking Process. Flexicoking involves coking the heavy residuals to form a distillate gas oil and then gasifying the coke which contains the sulfur. The sulfur, present as H_2S, is removed in a sulfur recovery unit and the resultant gas may be used in furnaces or boilers. The first commercial Flexicoker is being constructed in Japan with a capacity of 22,000 bbl/day. It is scheduled for start-up in 1976. Since April 1974, a prototype, 750 bbl/day Flexicoker has been processing various feeds at the Exxon Company, USA, refinery in Baytown, Texas. Performance has equalled or surpassed expectations (Ref. 3).

Other processes for desulfurizing residual oils involve the development and use of poison-resistant catalysts in the reactors used for hydrodesulfurization.

3.4 Flue Gas Cleaning

Since 1967 considerable work has been underway to develop systems to remove SO_2 from power plant effluent gases. Processes which have been developed to remove SO_2 from power plant stack gases can be generally divided into two categories--"throwaway" and "by-product recovery." Throwaway processes involve SO_2 absorption and combination with some cation (generally calcium, sodium, or ammonia). This combination is precipitated as a solid and disposed of as a waste material. In by-product recovery processes, flue gas SO_2 is absorbed, recovered, and then marketed in the form of liquid or gaseous SO_2, sulfuric acid, elemental sulfur, sodium sulfate or ammonium sulfate.

The majority of full-size power plant desulfurization systems in both the planning and operational phases involve lime or limestone wet scrubbing systems. These processes will be discussed at some length in this section with regard to principles of operation, status of development, operability, and reliability. A number of by-product recovery processes are currently undergoing investigation at both the pilot plant and full-scale levels of development. The more advanced of these systems will be examined in the sections following.

3.4.1 Lime/Limestone Wet Scrubbing Technology - Throwaway processes using lime and limestone as the alkaline absorbent have been the target of the greatest part of the research and development efforts in SO_2 control. Primary reasons for this are that these processes are more fully characterized than other first generation systems; have relatively low capital and operating costs; and have relatively high potential removal efficiencies (90-95 percent).

Two basic types of wet limestone processes have been developed: (1) boiler injection of the limestone followed by wet scrubbing, and (2) addition of limestone into the slurry handling system (tail-end scrubbing process).

The boiler injection plus wet scrubbing process has been extensively tested on a commercial scale by Combustion Engineering, Inc. (CE) since 1968. After 4 years of intermittent operation due to numerous technical difficulties, CE no longer offers this process in favor of the lime/limestone tail-end scrubbing process.

In the tail-end addition process, lime or limestone is added directly to the slurry circuit rather than injected into the boiler. The overall reaction in the scrubbing system involves gaseous SO_2 and CO_2 reacting with CaO or $CaCO_3$ to give solid $CaCO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$, lime or limestone, and fly ash from the system.

The first full-scale installation in this country that utilizes limestone introduced into the scrubbing circuit is the 175 Mw Commonwealth Edison Will County Station - Unit No. 1. This unit was started up in February 1972, and has operated intermittently since then, achieving SO_2 removal efficiencies in the range of 75 to 85 percent. The major problems experienced to date have involved demister pluggage with a soft, mud-like substance, system reliability due to mechanical problems, and uneconomic disposal of waste sludge (Ref. 4). A great deal has been learned in the past year, however, at the Will County Unit concerning practical operating problems with limestone scrubbing; during 1974 the availability of one of the two modules steadily increased. None of the problems encountered at this unit appears to be insurmountable.

Additional valuable information concerning operation of lime/limestone scrubbing processes is being gathered at the versatile EPA prototype test facility at the TVA Shawnee Steam Plant. The 30 Mw facility includes three types of 10 Mw (equivalent) scrubbers (venturi, TCA, and marble bed), extensive process instrumentation, and sophisticated data acquisition and handling systems. Water and soda ash and short-term lime and limestone testing have been completed; long-term reliability limestone and lime testing are in progress (Ref. 5).

The most recent successful operation of a lime wet scrubbing process is the 65 Mw installation at Louisville Gas and Electric Company's Paddy's Run Station. The unit uses carbide sludge [$Ca(OH)_2$] as the alkaline absorbent. No scaling or plugging problems have been encountered in over 3000 hours of closed-loop operation since April 1973. The system demonstrated near 100 percent availability during the last 4 months of 1974 while removing 80 to 90 percent of the flue gas from boilers fired with 1.5 to 4.0 percent sulfur coal (Ref. 6). Waste sludge is thickened, filtered and disposed of as untreated landfill; fly ash is sporadically mixed in by bulldozers at the disposal site.

Much of the developmental work with the lime scrubbing system has been conducted in Sweden and Japan. The A. B. Bahco system, which utilizes a two-stage inspirating scrubber, is considered an important operational scrubber facility despite its small size (the equivalent of about 25 Mw for the three units). The system has been operating routinely at 95 to 98 percent SO_2 removal on three oil-fired boilers at a Stockholm hospital. The unit is considered among the more successful wet lime scrubbers although periodic shutdowns are necessary to remove hard sulfate scale in the demister section. The demisters have not been equipped with washing sprays, a possible solution to the scaling problem. Research-Cottrell is the U.S. licensee for the Bahco process and is offering modules up to 40 Mw. EPA has recently entered into an agreement with the Air Force for a Bahco process test program to be conducted on a seven-boiler installation with a total 25 Mw (equivalent) capacity.

In Japan the 156 Mw power plant of the Mitsui Aluminum Company has been retrofitted with two Chemico dual-stage venturi scrubbing systems, each capable of handling 75 percent of the full load gas flow. The system has demonstrated reliable, trouble-free operation since being put on stream in March 1972 The plant is presently burning 2 percent sulfur coal (1800 to 2200 ppm inlet SO_2) and achieving 80 to 85 percent SO_2 removal from the flue gas using carbide sludge as the alkaline absorbent. Since coming on stream, the system has operated at near 100 percent availability. The absence of scaling difficulties has been attributed to operational know-how developed by Mitsui in extensive pilot plant tests (in Japan) and precise pH control. To date the Mitsui system is the most successful operating unit based on a throwaway process (Ref. 4).

A survey of the seven companies with experience in full-scale tail-end wet scrubbing shows that most companies will provide SO_2 removal quantities varying from 70 to 90 percent, or as required to meet EPA standards (Ref. 4). A number of important design variables have changed in range since the first systems were built 5 years ago. The liquid to gas ratio has increased from 35 liters/1000 N cubic meters (10 gal./1000 acfm) to as high as 350 liters/1000 N cubic meters per hour (100 gal./1000 acfm), with the average being near 210 liters/ 1000 N cubic meter per hour (60 gal./1000 acfm). Stoichiometry has decreased to near 1.0 from a former average near 1.75 based on SO_2 absorption. Values for both weight percent solids in the scrubbing slurry and hold tank residence times vary among suppliers but the general trend has been toward higher values. Systems can be designed for units firing from 0.5 to 4.0 percent sulfur fuel and ranging in size up to 800 Mw. Module designs are limited to about 150 Mw (Ref. 4).

3.4.2 Magnesium Oxide Scrubbing - All of the magnesia-based (MgO) processes may be classified as by-product recovery in that they produce sulfur-based products (H_2SO_4 or liquid SO_2) which do not contain the additive (MgO).

In the Chemico-Basic Chemicals version of the process, flue gas containing SO_2 and fly ash passes into a venturi scrubber where fly ash is removed by scrubbing with recirculated water. A bleed stream from the scrubber is thickened to concentrate the fly ash and transported as a slurry underflow to the disposal area. Overflow from the thickener is returned to the scrubber circuit. Flue gas leaving the particulate removal system enters a second venturi absorber where it contacts a slurry of MgO and recycled $MgSO_3$, and $MgSO_4$ and unreacted MgO are separated from the mother liquor. Mother liquor is recycled to the scrubber and the centrifuged wet cake is dried in a rotary kiln. Dried anhydrous crystals are sent to a central plant where they are calcined to recover MgO and SO_2. The MgO is re-slurried to maintain SO_2 sorption in the scrubber.

Chemico-Basic Chemicals is the leading developer of the MgO process, based on the EPA cofunded system installed on a 155 Mw oil-fired unit of Boston Edison's Mystic Station. Regeneration of MgO and production of H_2SO_4 is being carried out at Essex Chemical Company. A similar system has been installed to treat 100 Mw (equivalent) of flue gas from a coal-fired boiler at Potomac Electric and Power's Dickerson No. 3 Unit. The Dickerson plant has shown low, but improving, reliability with 88 to 96 percent SO_2 removal. The availability to the boiler was 60 percent for the months of August to November of 1974 (Ref. 7).

Experience with the MgO process to date has been encouraging but not wholly without problems. Because of various equipment problems, the Boston Edison installation operated only 20 percent of the time between April 1972 and June 1973. Since that time, however, the system has demonstrated considerably improved reliability. In the period of April 12 to May 10, 1974, 623 hours were logged at almost 100 percent availability. Since February 22, 1974, availability of the system to the boiler has been about 80 percent compared to 50 percent for the year from June 1973 to June 1974 (Ref. 8). A major technical problem encountered with this system concerns oxidation of sulfites to sulfates, thereby reducing regenerator efficiency. The SO_2 removal appears to be easily accomplished in the process. Some additional problems may arise with loss of reactivity of frequently regenerated absorbent, but this question can only be resolved with longer periods of continuous operation.

3.4.3 Wellman-Lord Process - Several developers have turned to sodium-based processes for flue gas desulfurization because sodium has a high affinity for SO_2 and the sulfite/ bisulfite equilibrium can be adjusted to facilitate absorption and regeneration.

In the Wellman-Lord process (offered by Davy Powergas), the most technically advanced of the sodium-based processes, flue gas from the boilers is first washed by a prescrubber to remove the greater part of the solids from the gas. The flue gas passes to an absorber where SO_2 is absorbed into a solution of sodium sulfite, bisulfite, and sulfate. The SO_2 combines with the sulfite to form bisulfite or else undergoes oxidation to form sulfate. Exiting the scrubber, the absorbent is heated in an evaporative crystallizer with steam to yield 90 percent SO_2 gas and sodium sulfite crystals which are recycled. The high purity, high concentration SO_2 gas can be further processed to liquid SO_2, sulfur, or H_2SO_4. Sulfate formed in the scrubber by oxidation cannot be regenerated and is removed from the system by direct purging or selective crystallization of sodium sulfate.

The major problem with the Wellman-Lord process is its sensitivity to buildup of contaminants necessitating bleed. The major contaminants are sodium sulfate, thiosulfate, and polythionates formed either by oxidation in the scrubber or a disproportionation reaction in the evaporative crystallizer. In Japanese installations these waste products are discharged to the ocean. Additional treatment will probably be required for application in the United States.

A significant demonstration of Wellman-Lord technology is by Mitsubishi Chemical Machinery at the Japan Synthetic Rubber's Chiba Plant. This unit has operated at almost 100 percent availability during the past 3 years while removing better than 90 percent of the SO_2 from a 75 Mw equivalent oil-fired boiler flue gas stream containing 600-2000 ppm SO_2. The main disadvantage of the system is the requirement to bleed a waste liquor stream due to sulfate formation. A new unit at the Chubu Electric's Nishingoya Plant has reduced this purge by a factor of 4. This unit has been operating reliably on a 200 Mw peak-shaving unit since May 1973.

EPA is currently co-funding construction of a Wellman-Lord process installation on the 115 Mw Northern Indiana Public Service Company's Mitchell Station in Gary, Indiana. A 1-year demonstration is planned with start-up scheduled for late 1975. This will be the first application of the Wellman-Lord process to coal-fired boilers The plant will also demonstrate the technology for reduction of SO_2 to elemental sulfur with an integrated Allied Chemical Company process.

3.4.4 Catalytic Oxidation Process - Two distinct catalytic oxidation (Cat-Ox) schemes are available. The reheat Cat-Ox system is an add-on unit designed for use on existing power plants. The integrated Cat-Ox system, on the other hand, is for incorporation into the design of new power plants.

In the reheat system, particulate removal from the hot flue gases from the boiler is accomplished by a high efficiency electrostatic precipitator. In preparation for catalyst conversion, the flue gas stream is heated by a series of oil- or gas-fired reheater burners and heat exchangers. At proper temperature (454°C (850°F)) for improved reaction kinetics, the flue gas is sent to a fixed bed converter where SO_2 is oxidized to SO_3 in the presence of a V_2O_5 catalyst. Sulfuric acid is formed by contacting the SO_3 rich gas with water in an absorption tower after the gas has been cooled by heat exchange. The product acid (75 to 85 percent sulfuric) is cooled and sent to storage. Flue gases are vented to the atmosphere after passing through a fiber-packed mist eliminator. The process removes essentially all particulate matter and 85 percent of the inlet SO_2.

The integrated Cat-Ox system does not require reheat procedures because the overall design of the plant provides for the flue gases to exit the boiler at the conversion temperature. The gases go immediately to the converter after electrostatic precipitation to remove ash. After the converter, the energy of these hot gases is utilized in a heat exchanger section, which consists of an economizer and an air heater. Other process steps are nearly identical. In this process, 90 percent of the SO_2 and essentially all particulate matter are removed.

Pilot plant work on this process was begun in 1961. A prototype (15 Mw) unit was installed at Metropolitan Edison's Portland Station in 1967, removing 90 percent of the SO_2. EPA, Monsanto (the process developer), and Illinois Power Company have been involved in the installation of a reheat demonstration plant on a 100 Mw boiler at Wood River, Illinois. The installation was originally started up in September 1972. Preliminary operations in September and October 1972, using gas as the reheat fuel, indicated that the unit was meeting the performance criterion of greater than 85 percent net SO_2 removal. In October 1972 it became evident that the shortage of natural gas would preclude its use as reheat fuel for the burners. It was, therefore, necessary to modify the burner equipment to fire oil exclusively the system was returned to operation on August 14, 1974. Mechanical and structural problems have caused sporadic operation since then.

Typical operating problems at Wood River may include plugging of the catalyst bed with fly ash, catalyst attrition during cleaning, and fly ash build-up in the final mist eliminator. There would be fewer problems with oil-fired units than with the coal-fired units because less fly ash is present in the former. Reliable precipitator operation seems to be particularly important for coal-fired plants since heavy particulate loading can cause catalyst plugging and poisoning. The moisture content in normal flue gas limits direct acid production to a yield of 70-80 percent H_2SO_4, a less desirable by-product than either pure acid, sulfur, or SO_2 gas.

3.4.5 Double-Alkali Process - A variation of both the sodium- and ammonia-based scrubbing processes is the double alkali process. Here sulfur dioxide is scrubbed with a clear liquor of sodium or ammonium salts and the resulting solution is treated with lime or limestone to precipitate calcium salts for disposal and to regenerate sorbent.

General Motors (G.M.) is a leading developer of the double-alkali process in this country. G.M. is currently testing a full-scale, industrial size system at its Chevrolet-

Cleveland Plant based on its pilot plant results achieving 90 percent SO_2 removal from a 4700 m^3/hr (2800 cfm) stream (Ref. 9). Combustion Equipment Associates, Inc. and Arthur D. Little, Inc. have jointly designed and built a dual alkali prototype system at Gulf Power Company's Scholz Station. The system is designed to operate at a 20 Mw full load with the boiler firing 5 percent S coal. Testing is scheduled for early 1975. A good deal of work has been done in Japan by Showa Denko and Kureha Chemical using sodium sulfite as the absorbent and limestone as the regenerant. Other absorbents besides Na_2SO_4 have been investigated: NH_4OH by EDF-Kulhmann; dilute H_2SO_4 by Chiyoda; and an undisclosed organic compound by Monsanto.

Although the double-alkali processes are designed to avoid scaling problems in the scrubber, the possibility is not completely eliminated because a saturated $CaSO_4$ solution still may be returned to the system. This problem may be avoided by use of a number of techniques designed to lower the dissolved solids concentration of the regenerated scrubbing liquor.

Although development work in this area has been intense, the process has not been demonstrated on large, coal-fired boilers over extended periods of operation.

3.4.6 Other Flue Gas Cleaning Systems - A number of additional systems are at various stages of application; some are being offered for commercial applications and others are in earlier stages of development. Those being offered for demonstration include char sorption systems by Foster-Wheeler and Commonwealth Associates, sodium solution scrubbing systems with electrolytic regeneration by Stone and Webster/Ionics, and a dry sorption system by Esso Research and Engineering and Babcock and Wilcox.

A number of other processes have not reached the point of being offered for full-scale application but are presently being studied. North American Rockwell is developing a molten carbonate scrubbing system, which reacts an eutectic mixture of lithium, sodium, and potassium carbonates with SO_x. Testing is being performed on a 10 Mw (equivalent) pilot plant, in cooperation with Consolidated Edison. The Bureau of Mines has investigated a sodium citrate scrubbing process that produces by-product sulfur.

Ammonia scrubbing of stack gases with ammonium sulfite and bisulfite is being studied in field pilot-scale trials by EPA and TVA. Monsanto is researching an ammonia scrubbing system. Organic absorbents in aqueous solutions are also being studied by Monsanto. Two systems, one with thermal regeneration, are said to be under development.

A char sorption system which incorporates reducing gas regeneration is being developed by Westvaco with the support of EPA.

U.O.P. is working to develop a proprietary aqueous process which produces sulfur as a by-product. The process is being studied in cooperation with Commonwealth Edison on a 20 Mw pilot plant.

3.5 Fluidized Bed Combustion

Several types of fluidized bed combustion systems are under development. A chemically active fluidized bed which gasifies/desulfurizes residual oil at atmospheric pressure in a fluidized bed of limestone is being developed at Esso, Ltd. (England) with support by EPA. Coal-fired pressurized fluidized bed systems with limestone are also under development in the United States where EPA is supporting work at the Westinghouse R&D Center, Argonne National Laboratory, and Esso Research and Engineering. USDI's Office of Coal Research (OCR) is supporting a 30 Mw demonstration of an atmospheric coal-fired fluidized bed. The EPA work with coal in limestone beds is being conducted on bench and pilot scale, and a number of process concepts (pressurized, regenerable, nonregenerable) will be evaluated. EPA has also studied the concept of using fluidized bed systems equipped with sulfur oxide scrubbing systems for use in disposal of high ash, high sulfur residues produced by other coal processing systems.

Fluidized bed systems are attractive for their ability to control both sulfur oxides and nitrogen oxides, particularly in pressurized systems. In addition, their capability for burning very high ash materials makes them potentially useful for utilizing fuel residues and low grade fuels such as oil shales, which are becoming increasingly valuable.

3.6 Coal Gasification (High HV Gas)

Within the past 4 years, a great deal of money and energy has been directed at the development of a substitute or synthetic natural gas (SNG) process which will prove economic and reliable. Viewed by many as a nostrum to the United States' natural gas supply limitations, the production of SNG from coal faces a number of inherent obstacles--most having to do with coal's lower hydrogen content in comparison to other fossil fuels (Ref. 10). Development efforts are underway toward adapting commercially available low heating value (HV) gas systems to production of high HV gas. The Lurgi, Koppers-Totzek and McDowell-Wellman processes have been used commercially in Europe to produce low HV gas from coal. In addition, there are four new processes for coal gasification to high HV that have advanced to or are near the pilot stage of development (Ref. 11, 12). These processes (and their developers) are as follows:

1. Hygas (Institute of Gas Technology)

2. Bigas (Bituminous Coal Research)

3. Synthane (Bureau of Mines)

4. CO_2 Acceptor (Consolidation Coal Company)

The processes listed above basically differ in the mechanism of coal gasification and in gasification design, but they may be generalized as high temperature (400°C (742°F) to 1700°C (3092°F)) and high pressure (35-70 atm) operations. A high HV gas may be obtained following gasification with a methanation (or gas separation) step. However, methanation of gasifier effluent has yet to be demonstrated on a commercial scale of the magnitude contemplated. Conversely, a low HV gas may be obtained by substituting air for oxygen in the gasifier. This low HV gas is suitable as boiler fuel or for use in combined gas-turbine/steam-turbine cycles (Ref. 10). Coal conversion to low HV gas is discussed in Section 3.7. The high HV processes are discussed below.

3.6.1 Modified Low HV Gasification Processes - Work is underway to adapt low HV systems to production of high HV gas. The low HV systems can be purchased now, but they have inherent characteristics which will limit their ultimate usefulness unless improvements are made. For example, the Lurgi system, which has found much usage throughout the world, can process only carefully prepared and sized noncaking coals. In addition, the sizes of modules which can be used are limited and these will need to be equipped with systems for flue gas cleanup and water pollution control.

3.6.2 Hygas Process - Basic Hygas process features in this design are the addition of hydrogen to the gasifier to promote methane formation and production of the required hydrogen by electrothermal gasification. However, several options are being investigated in lieu of electrothermal gasification. Coal is crushed, dried, and slurried in light oil before being sent to the gasifier. In the gasifier, one-half of the coal is devolatized and then gasified by heating to 925-980°C (1697-1796°F) in the presence of a hot, hydrogen-rich stream and steam. The remaining char is conveyed to an electrothermal gasifier where it is electrically heated in the presence of steam to form a gas mixture of hydrogen and carbon oxides. The gas stream is returned to the hydrogasifier (at about 1040°C (1904°F) and 57,000 mm Hg (1130 psi)) and the remaining char is burned in a power plant to provide the process with electrical energy and steam (Ref. 10).

A 68 metric ton/day (75 ton/day) pilot plant in Chicago began operation in 1972. The unit has experienced equipment materials and plugging problems that are being solved as operating experience is gained. Two additional designs are being prepared to generate the hydrogen-rich gas required by the process--steam/iron gasification and steam/oxygen gasification (Ref. 11).

3.6.3 Bigas Process - In the Bigas process, gasification of the coal feedstock occurs in two stages. In the first or upper section, about one-third of the coal is volatilized and reacted with synthesis gas from the lower stage to form a gas mixture and unreacted char. After separation in a cyclone, the gas mixture is purified and converted to SNG while the char is returned to the lower stage for gasification in the presence of steam and oxygen (Ref. 10).

Development work with this process was completed on a 45 kilogram/hour (100 lb/hr) internally fired process and equipment development unit in 1971. Since then, construction has begun on a fully integrated 4.6 metric ton/hour gasification pilot plant at Homer City, Pennsylvania. Initial start-up of the plant is planned for early 1975.

3.6.4 Synthane Process - In the Synthane process, developed by the Bureau of Mines, gasification occurs in three stages inside the gasifier. Char separated from the product gas is recycled to the lower part of the gasifier and ash is discharged from the bottom. Gas is sent through purification and methanation steps to produce a pipeline quality gas. A pilot plant for this process is now under contract.

3.6.5 CO_2 Acceptor Process - The heat necessary for gasification in the CO_2 Acceptor Process is supplied to the reacting coal by a circulating bed of heated dolomite. Gas leaving the gasifier may contain up to 20 percent methane and thereby eliminate the shift conversion step in the methanation process. This process has been specifically developed for use with lignite. A pilot plant now in operation at Rapid City, South Dakota processes 26 metric tons (30 tons) of lignite per day. After two years of operation, during which many mechanical problems were overcome, the pilot plant began producing useful process data. In the past year, a series of successful fully-integrated runs have demonstrated the technical feasibility of the process.

3.6.6 Schedule - With supplemental supplies of natural gas arriving from Canada and the Alaskan North Slope toward the end of the decade, it is unlikely that significant coal gasification to high HV gas will emerge before the 1980 to 1985 period (Ref. 13). The technology of gasification is generally too new to have much impact on gas prices prior to this same period.

3.7 Coal Gasification (Low HV Gas)

The Lurgi, Koppers-Totzek and McDowell-Wellman processes have had extensive commercial use in Europe to produce a low HV gas from coal. All of the coal gasification steps considered to have potential for incorporation in high HV systems are generally felt to be appropriate for improved production of low HV gas for production of power. Schemes for introduction of low HV gases into modified conventional boiler systems or into combined gas/steam cycles for power generation have only come under investigation within the past 2 years. Use in combined gas/steam cycles for power generation could be feasible with only minor advances in gas turbine technology.

Generally, processes which have been commercialized for some time are relatively costly for this application since they are operated at low pressure and throughput rates. Efforts have been underway to improve these operating conditions. Most of the developmental work to date has been with large atmospheric pressure combustion units.

The most advanced of the high pressure processes for low HV coal gasification is the Lurgi gas generator. In a fixed bed, coal is gasified with injection of air to produce a low temperature gas which can be washed to remove ash and tar. Hydrogen sulfide can be removed by commercially proven processes. In Germany, cleaned gas is then used in a steam-turbine/gas-turbine combined cycle power plant.

Of the high HV gasification processes described previously, the Bureau of Mines' Synthane process and the two-stage Bigas process of Bituminous Coal Research should be capable of substituting air for oxygen to produce low HV gas without major modifications.

It appears doubtful that endeavors to apply current low HV technology to high pressure, high throughput coal gasification will be economically significant before 1980.

3.8 Coal Liquefaction

In the past 2 years, coal liquefaction research has shifted in emphasis from processes aimed at the formation of a petroleum-type product from coal gasifier effluent to those producing a low sulfur, low ash liquid fuel suitable for boiler firing (Ref. 13). Several processes are currently under development with sponsorship from the OCR (USDI). One of these processes which has advanced to the pilot plant stage is discussed here.

The coal liquefaction pilot plant of OCR that is currently in operation involves the COED (char-oil energy development) process developed by FMC Corporation. The COED process involves coal pyrolysis to convert the feedstock into more valuable and pollutant-free products such as synthane, crude oil, gas and char. In the process, coal is volatilized in a series of fluidized bed reactors where it is reduced to its component parts. Gas from the process can be sold as fuel gas or converted to pipeline gas or hydrogen with the application of additional technology. Oil from pyrolysis is filtered to remove solids and hydrotreated at high temperature and pressure to remove sulfur, nitrogen, and oxygen. The product is a 25° API synthetic crude oil. Residual char can be used as power plant fuel, gasified to produce fuel gas, or processed to generate hydrogen (Ref. 11).

At this state of development, it is difficult to predict the size of the market that coal liquefaction products might attract in the next 10 years. On the basis of their infantile technology, however, it seems unlikely that these processes will have a major effect on the low sulfur fuel oil supply/demand balance before 1980 or 1985.

4.0 Economics of SO_2 Control Alternatives

An economic comparison of most of the SO_2 control alternatives discussed in Section 3.0 is presented in this section. The estimates, based on best available information, include capital and operating costs in consistent units. Cost analyses of emerging technologies are hazardous because of their evolutionary nature: estimates of capital and operating costs for processes only at the bench-scale or pilot phase of development may be speculation.

Future costs for naturally occurring clean fuels are perhaps the most difficult to predict due to the uncertainty of the supply and the market's response to diverse factors (e.g., stack gas desulfurization and import limitations). Fuel costs for gas, oil, and coal based on August 1974 data (Ref. 14) are summarized in Table I-5.

Because of past regulatory practices, natural gas is currently low in cost despite the desirability of this fuel. The natural gas costs reported in Table I-5 were based on a survey of over 500 utility contracts. This survey showed that unregulated intrastate gas was being sold for as much as 18 mills/Kwh while interstate regulated gas averaged 5 mills/Kwh. Since the majority of natural gas used by utilities is interstate, it is anticipated that if natural gas were deregulated prices would rise dramatically.

As shown in Table I-5, both naturally occurring and desulfurized residual and distillate fuel oil prices were higher than other fossil fuels regardless of sulfur content. Unlike natural gas, there was not a wide price range reported for fuel oil in the survey. Fuel oil containing approximately 1 percent sulfur was reported to be selling for approximately 18 mills/Kwh while 0.3 percent sulfur fuel oil was selling for 20 mills/Kwh.

Coal costs in Table I-5 range from 3.1 to 9.0 mills/Kwh depending on the sulfur content and the locality. Coal prices F.O.B. the plant are for Western coal used by Western utilities and Eastern coal used by Eastern utilities. It should be noted that most Western plants are minemouth plants and that transportation costs for Western low sulfur coal could be as much as \$0.51/metric ton-100 kilometers (about \$0.75/ton-100

Table I-5. ECONOMIC ESTIMATES FOR SO2 CONTROL ALTERNATIVES[a]
(1974 DOLLARS)

SO_2 Control Alternative	Availability For Application	Applicability To Existing & New Power Systems	Fuel Costs, mills/Kwh	Capital Costs	Annualized Control Costs, mills/Kwh	Effective Fuel Costs (Fuel Cost + Annualized Control Costs)
Low Sulfur Fossil Fuels						
Gas	Current	Limited availability; existing units only.	4.0-6.0	N/A	---	4.0-6.0
Oil	Current	Limited low-S avail.	18.0-20.0	N/A	---	18.0-20.0
Western Coal[b]	Current	Limited prod.; wide applic. to new boilers, limited existing applic.	4.0-6.0	N/A	---	4.0-6.0
Eastern Coal[b]	Current	Limited low-S avail.	4.5-9.0	N/A	---	4.5-9.0
Coal Cleaning						
Physical	Current	Limited: only ~ 25% S removal for most coals.	3.1-6.7[c]	$10/Kw	0.8-1.5	3.9-8.2
Chemical (Pyritic S Removal)	1978	Limited to pyritic coals; full applic. to exist & new.	3.1-6.7[c]	$26/Kw	1.55	4.7-8.3
Desulfurization of Oil						
1 wt % Sulfur Oil	Current	Full applicability for oil boilers.	15.0[d]	N/A	---	18.0
0.3 wt % Sulfur Oil	Current		15.0[d]	N/A		20.0
Flue Gas Desulfurization Process						
Double Alkali	1974	Wide applicability to most existing and new coal & oil boilers.	3.1-6.7[c]	$61/Kw	3.55	6.7-10.3
Lime Scrubbing	Current		3.1-6.7[c]	$45/Kw	2.90	6.0-9.6
Limestone Scrubbing	Current		3.1-6.7[c]	$50/Kw	2.86	6.0-9.6
MgO (to H_2SO_4)	Current		3.1-6.7[c]	$53/Kw	3.07	6.2-9.8
Wellman- Lord (to H_2SO_4)	Current		3.1-6.7[c]	$60/Kw	3.67	6.8-10.4
Wellman- Lord (to S)	Current		3.1-6.7[c]	$61/Kw	3.80	6.9-10.5
Cat-Ox	Current		3.1-6.7[c]	$85/Kw	3.44	6.5-10.1
Fluidized Bed Combustion[e]	1977-1978	Applicable only for new systems.	3.1-6.7	$308/Kw[f]	0.3-1.7[g]	3.4-8.4
Coal Gasification						
Low Btu Gas	Post 1980	Generally more applicable to new units.	3.1-6.7	$72-$109/Kw	---	8.3-12.8
High Btu Gas	Post 1980	Applicable to new & existing units.	3.1-6.7	$75-$125/Kw	---	12+
Coal Liquefaction	Post 1980	Applicable to new and existing units.	3.1-6.7	$60-$90/Kw	---	6.5-9.6

[a] As of November

[b] Costs are for Western coal delivered in the West and Eastern coal delivered in the East; additional costs for transporting Western coal to the East (or vice versa) are $7.50 per ton per 1000 miles.

[c] Coal cost is for high sulfur (3.0-4.0% S) Eastern coal.

[d] Oil cost is for 3.5-4.0% S crude oil.

[e] Pressurized fluid bed boiler combined cycle, once through system; coal.

[f] Includes power generation equipment.

[g] Control considered inherent in the boiler.

miles). For a typical 1600 kilometer (1000 mile) delivery, the F.O.B. plant cost for Western low sulfur coal delivered in the West, the cost would be 8-10 mills/Kwh.

Estimates of economics, availability for application, and applicability to the utility industry of current SO_2 control technologies are also summarized in Table I-5. While the individual values used in this comparison may not be absolute, the relative costs are considered representative. Each of these alternatives is discussed below.

Costs for physical coal cleaning, a currently available technology, were based on reports of U. S. Bureau of Mines (Ref. 15), Bituminous Coal Research (Ref. 16), and Paul Weir (Ref. 17). Costs for chemical coal cleaning were estimated by TRW (Ref. 18) based on a recently completed bench-scale study for EPA. Estimated capital and total annualized operating costs were \$26/Kw and 1.50 mills/Kwh for a 225 Mw plant operating at about 75 percent load factor. Capital costs for chemical cleaning were found to decrease with decreasing load factor.

Capital and operating expenses for flue gas desulfurization systems are somewhat easier to estimate since cost breakdowns are available from actual installations. Care must be taken, however, when quoting capital and operating costs to specify the basis on which they were made. This is true since costs for flue gas desulfurization are sensitive to size and age of the boiler, flue gas scrubbing rate, sulfur content of inlet gas, load factor, waste disposal costs, and by-product credits, among other factors.

McGlamery (Ref. 19) has prepared comparative process costs for seven of the eight flue gas desulfurization processes discussed in preceding Section 3.0. (Cost estimates are not yet available for the B&W-Esso process.) These costs included in Table I-5 are for a new installation of the processes at a 500 Mw generating station operating an average of 4250 hr/yr over a 30 year life and burning 3.5 percent sulfur coal. Waste disposal costs were taken to be $3/metric ton wet sludge. A $25/metric ton by-product sulfur credit and an $8/metric ton by-product sulfuric acid credit are allowed.

Annualized costs for flue gas desulfurization processes are estimated between 3 and 4 mills/Kwh, with a mean near 3.5 mills/Kwh. These costs can be considered typical for comparison with other SO_2 control technologies.

Fluidized bed combustion of coal will apply only to new units. Westinghouse (Ref. 20) estimated capital and annualized operating costs at $308/Kw and 7.67 mills/Kwh (excluding fuel costs), respectively, for a coal-fired, 635 Mw pressurized, once-through, fluid bed boiler, combined cycle. Load factor was 70 percent and no credit for sulfur was included. Since these costs are for a new unit they take into account equipment costs common to conventional units. As such, they cannot be compared directly with other control alternatives. However, the capital cost approximates that for a conventional boiler plus SO_2 control by FGD. On this basis, annualized control costs have been estimated to be zero-1.7 mills/Kwh.

Coal gasification technology presents an alternative which may, in the long term, become economically competitive with flue gas cleaning. Production of low HV gas by the Lurgi process would require capital investments of about $180 to $190 million for a 7 million cubic meter (250 million cubic foot) per day plant (Ref. 21). Operating costs for this process are particularly high. The selling price of SNG from a Western low sulfur semibituminous coal is expected to be approximately 12.5 mills/Kwh (Ref. 11, 22). Lower costs are expected for advanced low HV gasification processes using higher temperatures and pressure.

High HV gasification processes producing pipeline quality gas are expected to be even more expensive than low HV gasification schemes. Capital investment estimates for the four high HV gasification processes discussed in Section 3.6 vary from $200 to $230 million for a 7 million cubic meter (250 million cubic foot) per day facility. The cost of pipeline gas from these processes is expected to be more than 12 mills/Kwh (Ref. 23).

Gage (Ref. 24) has discussed the status of various coal liquefaction processes and indicated that the technology was in an early state of development. It was estimated that capital costs would be in the $ 60-90 /Kw range and energy cost would be in the 6.5-9.5 mills/Kwh range. M. W. Kellogg has reported operating costs of 10.0-13.0 mills/Kwh for an SRC process on an existing 500 Mw boiler (Ref. 22).

5.0 Economic Comparison of Regenerable Versus Nonregenerable FGD Processes

Figure I-1 is presented to illustrate the bounds on the economic comparison of regenerable FGD with throwaway FGD. The figures show lime/limestone process costs as a function of sludge disposal costs relative to regenerable processes.

Sludge disposal methods, for which costs are estimated, are unlined ponding, lined ponding, chemical treatment (fixation)

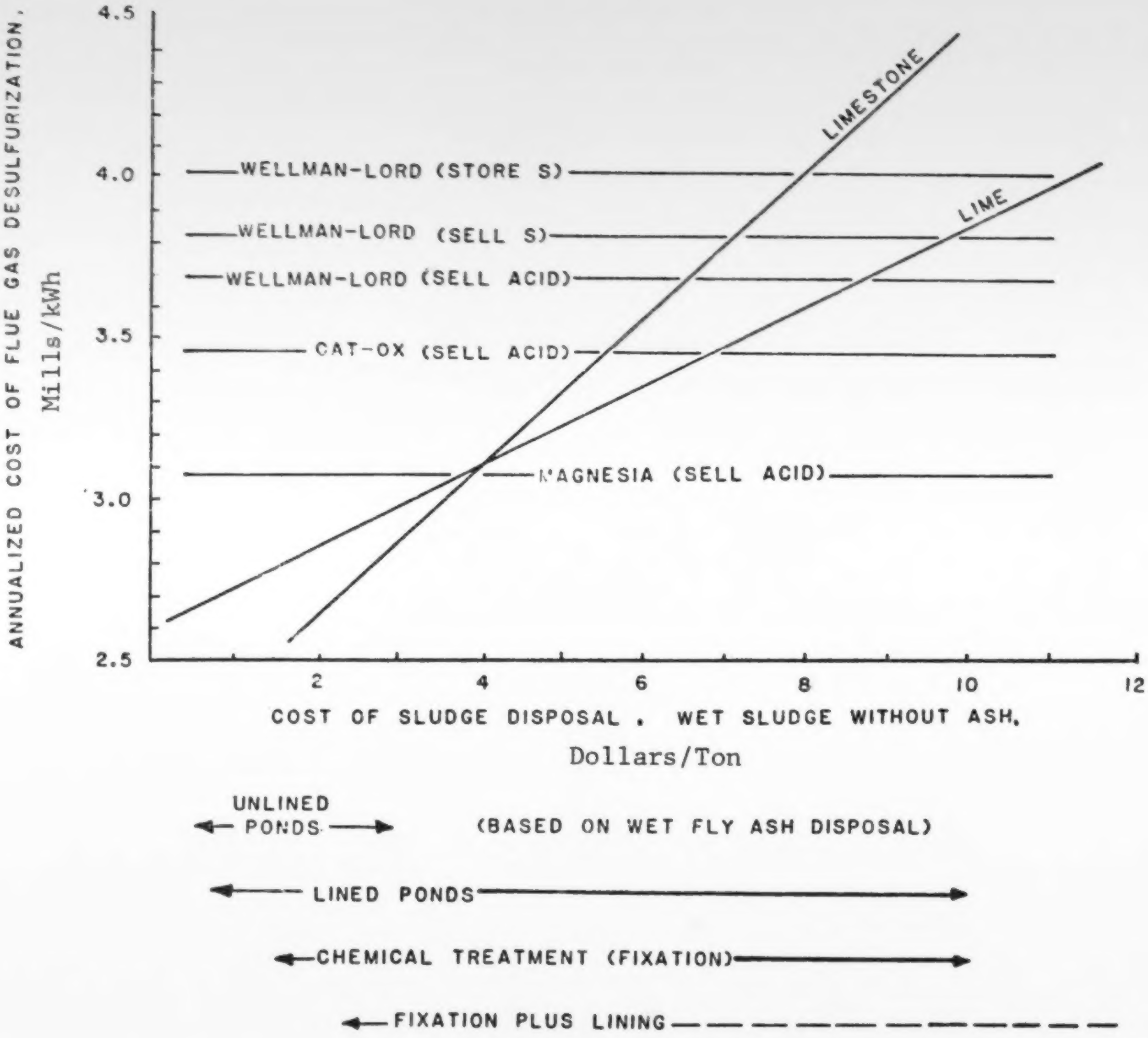


Figure I-1. Process Cost Comparison for Nonregenerable and Regenerable Flue Gas Desulfurization Systems--Effect of Sludge Disposal and By-product Sales or Disposal (Without Fly Ash).

and landfilling, and fixation plus lined landfill. The approximate ranges of sludge disposal costs included in the figure generally indicate an apparent minimum representing ideal circumstances, and an extension to the extreme right reflecting a broad range and our lack of knowledge regarding a reasonable upper limit.

The cases considered for comparison are MgO with the sale of acid, Cat-Ox with the sale of acid, and sodium systems with the three possibilities of the sale of acid, the sale of sulfur, or the storage of sulfur.

The process cost lines represent the center lines of bands 0.4 mills/Kwh wide reflecting a tolerance of approximately ±10% to account for plant to plant variability (even with a fixed basis) and lack of estimate precision. The estimates were based on the following assumptions:

1. Cost estimates are made on the basis of a 500 Mw new plant burning 3.5% S coal with an average load factor of 4250 hr/yr over a 30 year life.

2. Process costs are not for a first of a kind installation requiring extensive R&D, debugging, or reconstruction expenditures. Such expenses as first year operation, all R&D and other expenses frequently included in utility capital cost estimates, are not included.

3. Sludge and ash are produced at the rates given in Table I-8, Case 5.

4. For a given process, it is 0.15 mills/Kwh more expensive to produce elemental sulfur than sulfuric acid. This cost would be slightly higher for Mag-Ox than for Wellman-Lord.

5. Both acid and sulfur would sell for \$25/ton sulfur.

6. It costs \$2/dry ton or 0.02 mills/Kwh to store elemental sulfur.

Figure I-1 presents the case in which the utility's ash collection and disposal system is separate from the lime/limestone scrubbing and sludge disposal system. If ash will be disposed of separately or if no ash is required for fixation, this figure presents the lower bounds on lime/limestone process costs. The following observations can be made:

1. Assuming the existence of a market for the products produced by regenerable systems, lime scrubbing is less expensive than the regenerable systems considered below sludge disposal costs of about \$4/wet ton. Lime scrubbing is competitive with the regenerable systems up to disposal costs of about \$10/wet ton. In the case of storage of sulfur from a sodium system, lime scrubbing is still

competitive at costs greater than $11 per ton. Lime scrubbing is more expensive than MgO (sell acid) at any expected fixation cost.

2. Assuming the existence of a market for by-products, limestone scrubbing is less expensive than the regenerable systems considered below a disposal cost of about $4/wet ton. Limestone scrubbing is competitive with the regenerable systems up to disposal costs of about $7/wet ton. Limestone scrubbing with disposal costs greater than $7/wet ton is competitive with the sodium process in which sulfur is stored. Limestone scrubbing is more expensive than MgO (sell acid) at any expected fixation costs.

It should be noted that the costs in Figure I-1 are presented primarily for general comparisons and for demonstrating the economic considerations impacting the choice between regenerable and nonregenerable FGD. For specific installations, sludge disposal cost crossovers could vary considerably.

B. POTENTIAL DEMAND FOR LIME/LIMESTONE SCRUBBING

1.0 Introduction

Of the leading commercially available processes for controlling sulfur emissions from fossil fuel-fired generating stations, lime/limestone scrubbing is the only one which produces a throwaway sludge. The potential demand for lime/limestone scrubbing must be assessed in order to determine the quantity of throwaway sludge that will be produced.

At present, the installation of flue gas desulfurization systems is demand-limited due to a number of factors such as lack of confidence in the ability of the vendors to perform as promised, anticipation that regulations may be altered in the near future, potential difficulties in raising capital and obtaining rate increases to cover expenses for pollution abatement, and the lack of suitably trained personnel in the utility industry to evaluate and operate scrubber systems. These factors are being altered with time, and familiarity with the technology is increasing. Questions of confidence in system reliability will be erased with time as the utilities observe smooth operation from existing systems. With increased demand pressure, the installation of scrubber systems will probably become supply-limited due to such factors as availability of capital, availability of engineering/design services, demand and supply of critical labor categories, availability of major equipment suppliers, effect of down time on reserve generating capacity, and vendor capability. These supply limiting factors result from the evolutionary stage of development of this technology. The demand and supply limiting factors mentioned above have been the subject of many reports prepared by and for the EPA (Ref. 23, 25, 26), and an in-depth study of these factors is beyond the scope of this report.

The trends in the degree of flue gas desulfurization system utilization and the types of systems which are presently favored by the utilities can be ascertained by analyzing present and planned flue gas desulfurization systems in the United States.

In Table I-6 the full-size scrubber systems planned or operating in the United States are listed according to process type with the plant size, start-up date, fuel, and SO_2 removal efficiency given for each plant. Based on the data in this table, the following observations can be made:

1. Presently, 43 flue gas desulfurization systems are planned or in operation; 29 are lime or limestone scrubbing units; four are sodium based (two of these are the Wellman-Lord process); four are magnesium oxide systems; one is a dry system (Cat-Ox); and five are fly ash scrubbing systems with provisions for conversion to lime/limestone or sodium-based scrubbing.

2. The majority of the systems are installed on coal-fired units; only three of the 43 systems are on oil-fired units.

3. The total megawatts represented by these units is about 24,000.

4. The majority of the systems (by number) are retrofitted onto existing boiler facilities. The majority of capacity, however, is on new plants.

5. Presently, about 9,000 Mw of control capability is scheduled to be installed as of 1975.

Table I-6. PLANNED AND OPERATING FULL SIZE FLUE GAS DESULFURIZATION FACILITIES IN THE UNITED STATES[a]

	Utility Company/Plant/New or Retro	Plant Size, Mw	Start-Up	Fuel	SO_2 Removal Efficiency, %
	Lime/Limestone Scrubbing				
1.	Kansas Power & Light/Lawrence No. 4/Retro	125	December 1968	3.5% S Coal	70-75
2.	Kansas Power & Light/Lawrence No. 5/New	430	November 1971	3.5% S Coal	70-75
3.	Commonwealth Edison/Will County No. 1/Retro	163	February 1972	3.5% S Coal	75-85
4.	City of Key West/Stock Island/New	37	February 1973	2.75% S Oil	85 (expected)
5.	Kansas City Power & Light/ Hawthorne No. 3/Retro	130	November 1972	3.5% S Coal	70
6.	Kansas City Power & Light/ Hawthorne No. 4/Retro	130	August 1972	3.5% S Coal	70
7.	Louisville Gas & Electric/Paddy's Run No. 6/Retro	70	April 1973	3.5% S Coal	80+
8.	Kansas City Power & Light/LaCygne/New	820	June 1973	5.25% S Coal	80 (expected)
9.	Detroit Edison/St. Clair No. 6/Retro	170	December 1973	3.7% S Coal	82
10.	Arizona Public Service/Cholla/Retro	115	October 1973	0.4-1% S Coal	Uncertain
11.	Duquesne Light Co./Phillips/Retro	100	October 1973	2.0% S Coal	80
12.	Southern California Edison & other Southwestern Utilities/Mohave No. 1/Retro	160	December 1973	0.5% S Coal	Uncertain
13.	Southern California Edison & other Southwestern Utilities/Mohave No. 2/Retro	160	1974	0.5% S Coal	Uncertain
14.	Ohio Edison & others/Bruce Mansfield/New	1650	1975	4.3% S Coal	90+
15.	Montana Power/Colstrip No. 1 & 2/New	720	1975	0.8% S Coal	Uncertain
16.	Tennessee Valley Authority/Widow's Creek No. 8/Retro	550	1975	3.7% S Coal	80
17.	Louisville Gas & Electric/Cane Run No. 4	178	1975		
18.	Kentucky Utilities/Green River No. 1, 2, 3	64	1975		
19.	Northern States Power/Sherburne County No. 1 & 2/New	1360	1976, 1977	0.8%-1.2% S Coal	50
20.	Southern California Edison & other Southwestern Utilities/Navajo No. 1, 2 & 3/New	2250	1976, 1977	0.3%-0.8% S Coal	Uncertain
21.	Public Service of Indiana/Gibson/New	650	1976	1.5% S Coal	80
22.	Potomac Electric & Power/Dickerson No. 4 & 5/New	1700	1976, 1977	2.0% S Coal	Uncertain
23.	Columbus & Southern Oil Electric/Conesville	750	1976	Uncertain	90
24.	Arizona Public Service/Four Corners No. 1-5/Retro	1180	1976, 1977	0.75% S Coal	Uncertain
25.	Southern Public Service/Harrington No. 1	343	1976		
26.	Springfield Missouri/Southwest No. 1	200	1976		
27.	Texas Utilities/Martin Lake No. 1-4/New	3172	1976-1979		
28.	Louisville Gas & Electric/Mill Creek No. 3	425	1977		
29.	Kansas Power & Light/Jeffrey No. 1-4	2800	1979		

Table I-6 (Continued). PLANNED AND OPERATING FULL SIZE FLUE GAS DESULFURIZATION FACILITIES IN THE UNITED STATES[a]

	Utility Company/Plant/New or Retro	Plant Size, Mw	Start-Up	Fuel	SO_2 Removal Efficiency, %
	Sodium Base Scrubbing				
30.	Nevada Power Co./Reid Gardner No. 1 & 2 Retro[b]	250	1973	0.5-1% S Coal	83-92 (50 ppm outlet)
31.	Northern Indiana Public Service Co./D.H. Mitchell No. 11/Retro (Wellman-Lord)	115	1975	3.5% S Coal	90 (200 ppm outlet)
32.	Public Service Co. of New Mexico/San Juan No. 1 & 2 Retro (Wellman-Lord)	715	1977	0.8% S Coal	Uncertain
33.	Nevada Power Co./Gardner No. 3	125	1975		
	Magnesium Oxide Scrubbing				
34.	Boston Edison/Mystic Station No. 6/Retro	150	April 1972	2.5% S Oil	90+
35.	Philadelphia Electric Co./Eddystone No. 1/Retro	120	1974	2.5% S Coal	Uncertain
36.	Potomac Electric & Power/Dickerson No. 3/Retro	100	1974	3.0% S Coal	90
37.	Potomac Electric & Power/Chalk Point No. 3 & 4/New	1260	1975, 1976	Oil	Uncertain
	Cat-Ox				
38.	Illinois Power/Wood River/Retro	100	September 1972	3.25% S Coal	85
	Fly Ash Scrubbing[c]				
39.	Public Service of Colorado/Valmont No. 5/Retro	100	October 1971	0.8% S Coal	40
40.	Public Service of Colorado/Cherokee No. 1/Retro	125	June 1973	0.5% S Coal	35
41.	Public Service of Colorado/Cherokee No. 3/Retro	150	October 1972	0.5% S Coal	20 (expected)
42.	Public Service of Colorado/Cherokee No. 4/Retro	350	August 1974	0.5% S Coal	20+
43.	Public Service of Colorado/Arapahoe No. 4/Retro	100	September 1973	0.8% S Coal	35

[a] Ref. 27

[b] Once-through sodium scrubbing

[c] Provisions for conversion to lime/limestone or sodium-base scrubbing

6. The average fuel fired contained 3 percent S.

7. The average SO_2 removal efficiency is roughly 80 percent.

The installed capacity for flue gas desulfurization systems would appear to be no more than 10,000 Mw in 1975 since 2 to 3 years design and construction time for a system would require that essentially all systems that will be operational in 1975 be on order in 1973. The systems presently contracted to be installed by 1979 would bring the total megawatts controlled up to 24,000. This amount could be increased substantially if the institutional barriers presently causing installation of systems to be demand-limited were removed and the utilities were to make decisions to install such systems in the next few months.

2.0 Availability of Alternatives

During the period between now and 1980, a number of SO_x control technologies will be available to the utility industry. These alternatives will include lime/limestone scrubbing, other flue gas desulfurization technology, fuel cleaning, and burning naturally clean fuels. The utilities will probably continue the current pattern of selecting wet scrubbing systems, with the majority of orders for lime/limestone throwaway systems. There will probably be a significant increase in the number of orders for regenerative processes above the near term trends as market studies of various geographical areas are completed and use of sulfur increases.

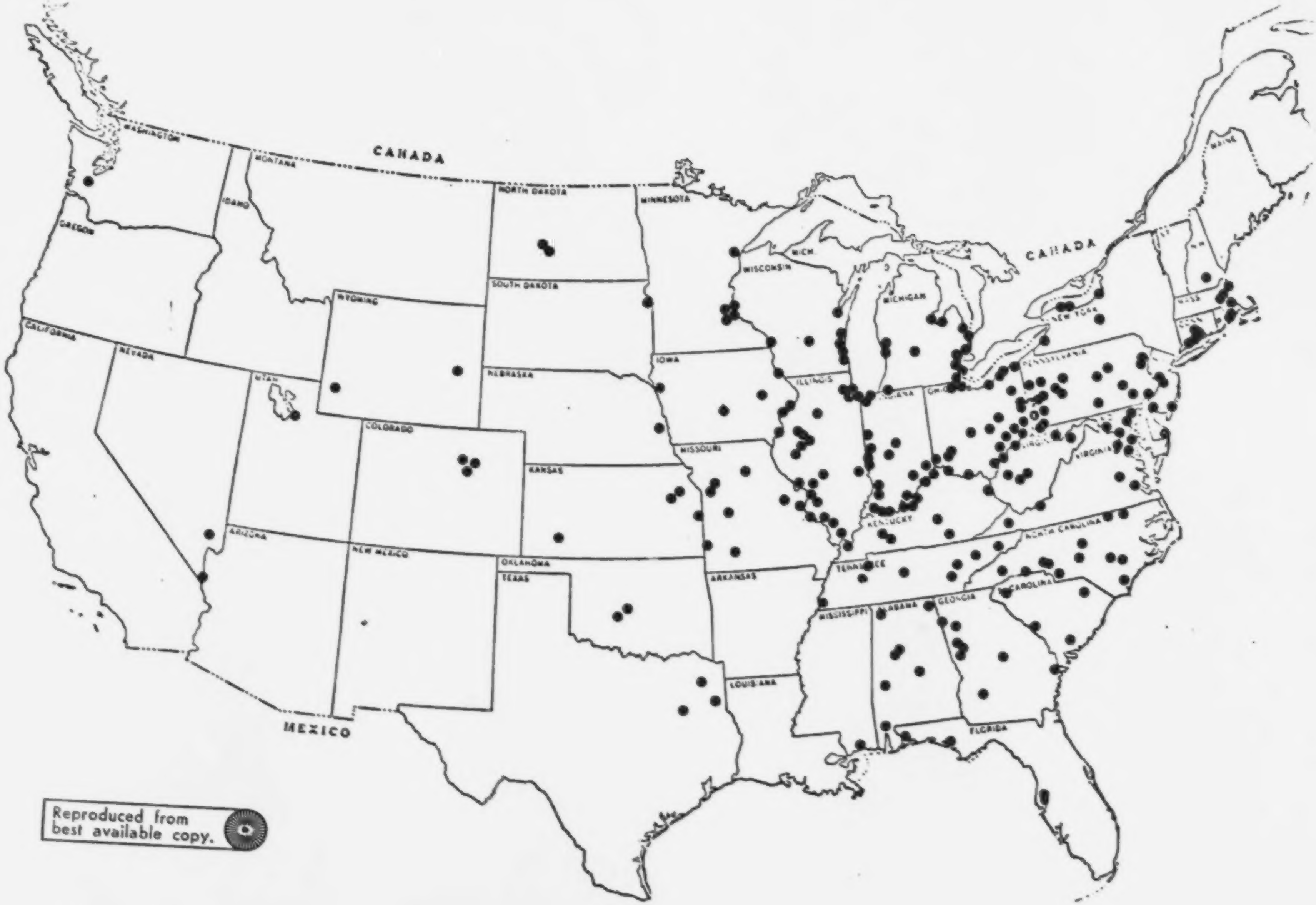
Processes such as liquefaction and gasification of coal will have insignificant applicability in the utility industry between now and 1980. Even the energy projection prepared by USDI (Ref. 1), the developers of most of the liquefaction/gasification processes, indicates that energy from these sources will provide less than 0.5 percent of the total United States energy demand in 1980.

Burning clean fuels (natural gas, low-sulfur oil, and low-sulfur coal) as an alternative to installing scrubbing systems will enjoy limited applicability in the utility industry. It is anticipated that greater than half the coal generating capacity and greater than one-third the oil-fired generating capacity in 1980 will have to be produced using high sulfur fuel. Switching fuels from coal or oil to natural gas, of course, will not be feasible.

Figure I-2 shows the location of coal-fired generating stations over 200 Mw in the United States. It is obvious from the map that the vast majority of the coal-fired generating capacity is located in the Eastern half of the Nation with the greatest concentration in the Northeast and East Central regions.

The majority of plants are located in regions rich in high-sulfur (3-4 percent) coal and far away from the major low-sulfur coal deposits in the West (mainly Wyoming and Montana). Transportation costs make the low-sulfur Western coal appear economically unattractive in many areas of the East, especially when the complexities of burning Western coal in some Eastern boilers not designed for Western coal are considered.

The East Central, West Central, South Central and Southeast sections of the country use tremendous amounts of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CALIFORNIA
NEVADA
IDAHO
MONTANA
UTAH
ARIZONA
WYOMING
COLORADO
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
MICH.
MICHIGAN
ILLINOIS
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
CAROLINA
NORTH CAROLINA
VIRGINIA
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MAINE

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Figure I-2. Coal-Fired Generating Stations Over 200 Mw in the United States (1971).

sulfuric acid in fertilizer production. A market survey recently completed by TVA concluded that abatement acid might penetrate the market with the proper price incentive by replacing sulfuric acid produced from purchased sulfur (Ref. 28). In view of this fact significant numbers of regenerable systems may be installed in these areas.

3.0 Projected FGD Need

Present uncertainties about alterations to existing compliance regulations and the time frames allowed for compliance with the 1970 Clean Air Act and state implementation plans should be resolved by legislation currently before Congress. While the time frame for compliance with NAAQS may change from the present 1975-1977 period, every effort will be made to meet the primary standards before 1980. No relaxation of the EPA standards for new plants is anticipated.

There are about 970 fossil fuel steam-electric plants operating in the United States, with a total generating capacity of about 302,000 megawatts (1972 figures). Of this capacity, roughly 55 percent or 166,000 megawatts are coal-fired and 17 percent or 51,000 megawatts are oil-fired (Ref. 29). Many of the oil- and coal-fired plants were already in compliance with applicable sulfur oxide emission limitations before current state implementation plans were developed. These plants had either undertaken control efforts, such as purchasing low-sulfur fuels, or were in areas where the sulfur dioxide ambient levels were not severe enough to warrant stringent emission limitations. Since the time when the implementation plans were approved, a number of additional plants have come or are coming into compliance by converting to fuels having lower sulfur contents and in some cases by installing FGD systems.

For the remaining noncomplying plants, EPA, in the January 1974 National Power Plant Hearings Report (Ref. 30), attempted to determine the amount of flue gas desulfurization that will be needed nationally to assure timely attainment and maintenance of primary ambient air quality standards. This analysis was performed by looking at the need through 1980 for FGD on new and existing coal-fired plants and for oil-fired plants expected to switch to coal. Due to the uncertainties in the oil supply situation, it was not possible to analyze the need to retrofit existing oil-fired plants with FGD systems.

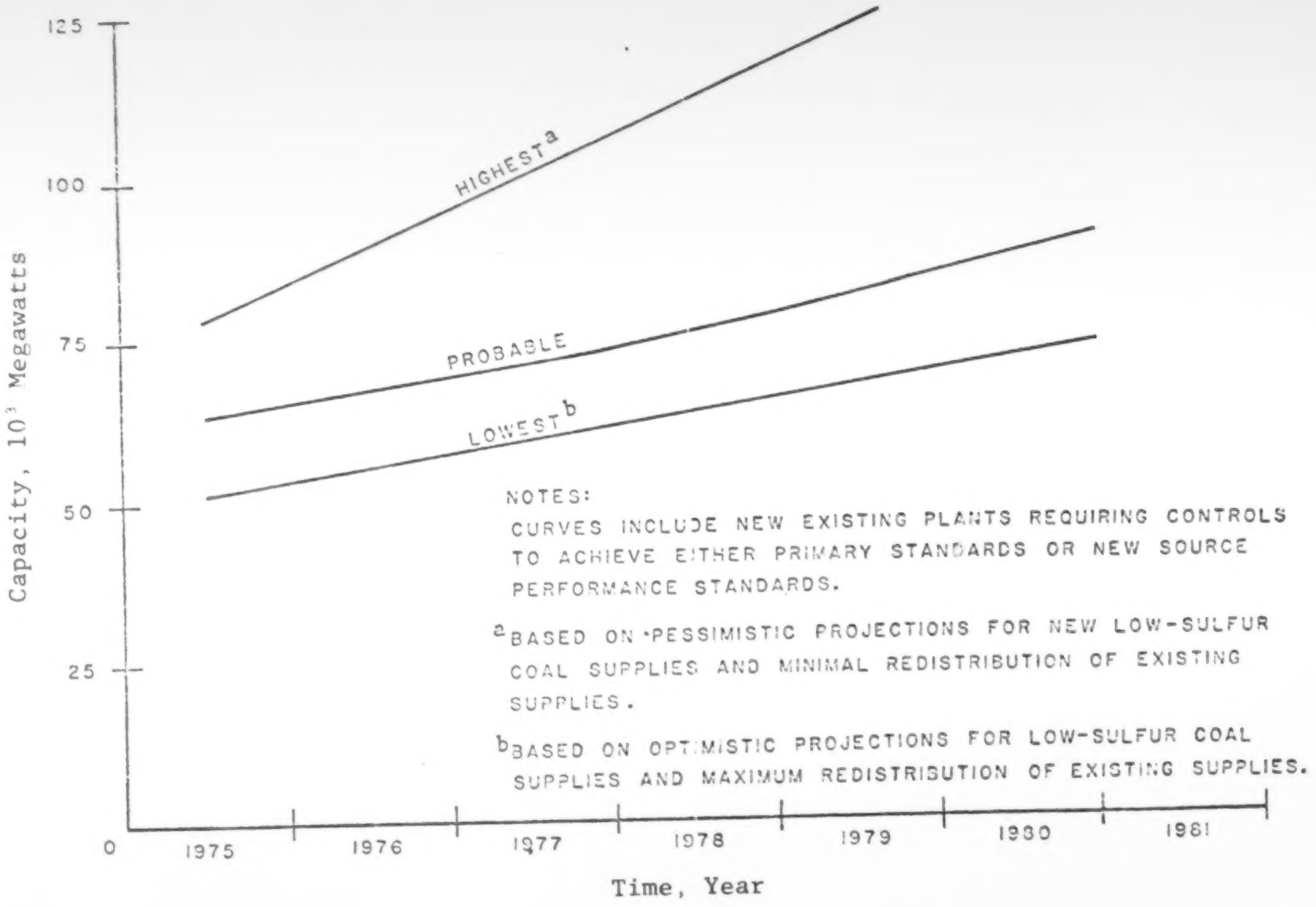
To quantify the need for FGD for existing coal-fired plants, EPA used diffusion modeling techniques to determine how many of these plants have an impact on attainment of the primary standards. The projected growth of United States coal-fired capacity from the 1972 level of 166,000 megawatts to 209,000 megawatts in 1975 (EPA estimate) was taken into account. Of this 209,000 megawatts, some 123,000 megawatts are not expected to need any emission reductions to achieve primary standards; 23,000 megawatts are expected to need moderate reductions through such techniques as washing currently used coal or blending this coal with low-sulfur coal; and 63,000 megawatts are expected to need substantial reductions either through the use of low-sulfur coal or FGD.

EPA estimated that an average of 24,000 megawatts of new fossil fuel capacity will come into operation each year after 1975. Of this, about 14,500 megawatts will be coal-fired. Since many of these plants will not be able to comply with state emission requirements or federal new source performance standards through the use of low-sulfur coal, they will greatly increase the need for FGD after 1975.

As indicated above, a number of plants now using oil are expected to switch to coal because of oil shortages. Most of these plants will need to apply FGD systems in order to ensure attainment and maintenance of primary standards. The estimated additional scrubber needs for plants switching from oil to coal were added by EPA to the needs calculated for existing and new coal-fired plants.

Some utilities will be able to obtain low-sulfur coal for their plants. New supplies of low-sulfur coal will not be significant between now and 1975; however, limited supplies will be available after that time. By distributing reserves and redistributing current supplies of low-sulfur coal to the areas where they are most needed to attain air quality standards, current and projected supplies could significantly reduce FGD requirements after 1975. For this reason, estimated new low-sulfur coal supplies were taken into account in the EPA analysis (Ref. 30).

The results of the analysis are displayed in Figure I-3. The curves in the figure show the maximum and minimum estimated FGD needs of those coal-fired power plants that need control for attainment of primary ambient air quality standards and attainment of EPA's new source performance standards. These curves include growth in coal-fired capacity from erection of new plants and expansion of existing plants, estimates of plants switching from oil to coal, the increase in supplies of low-sulfur utility coal, and the extent to which coal will be redistributed in response to SO_x emission limitations. Inherent in this analysis is the assumption that power plants having an impact on primary standards will have priority in the distribution of low-sulfur fuels and FGD systems.



NOTES:
CURVES INCLUDE NEW EXISTING PLANTS REQUIRING CONTROLS TO ACHIEVE EITHER PRIMARY STANDARDS OR NEW SOURCE PERFORMANCE STANDARDS.

[a] BASED ON PESSIMISTIC PROJECTIONS FOR NEW LOW-SULFUR COAL SUPPLIES AND MINIMAL REDISTRIBUTION OF EXISTING SUPPLIES.

[b] BASED ON OPTIMISTIC PROJECTIONS FOR LOW-SULFUR COAL SUPPLIES AND MAXIMUM REDISTRIBUTION OF EXISTING SUPPLIES.

Figure I-3. Cumulative Need: FGD for Coal-Fired Power Plants.

Although it is difficult to precisely determine the impact of the previously cited factors, especially the increased supply and redistribution of low-sulfur coal, the middle curve in Figure I-3 represents the most likely demand for FGD systems. As indicated by this curve, the cumulative need for FGD is about 66,000 megawatts by the end of 1975, 73,000 megawatts by the end of 1977, and 90,000 megawatts by the end of 1980.

It is important to note that there will be additional demands for FGD systems which were not included in the EPA analysis. For example, there will probably be an increasing demand for these systems to control many industrial boilers. In addition, the demand by oil-fired plants was not included in the analysis (Ref. 30).

4.0 Projected FGD Need Versus Vendor Capacity

In the January 1974 National Power Plant Hearings Report (Ref. 30), EPA also projected the capabilities of vendors to supply FGD systems between now and 1980. Two predictions of overall vendor capacity were discussed at the hearing: the Sulfur Oxide Control Technology Assessment Panel (SOCTAP) Final Report on Projected Utilization of Stack Gas Cleaning Systems by Steam-Electric Plants (Ref. 23) and the Industrial Gas Cleaning Institute (IGCI) survey and analysis (Ref. 30). In addition, some individual vendors discussed their capacity for future installation of scrubbers.

SOCTAP evaluated 15 sulfur oxide control system vendors and projected that three or four could expand rapidly and that another three or four could expand at a slower rate. The remaining seven to nine vendors were considered to have unproven abilities and the panel felt that they would not play an important role until the late 1970's. SOCTAP also predicted that some new vendors would enter the market. SOCTAP did use two "choke points" in their projections: one, the ability of the vendors to market their systems; and two, the ability of vendors to bring systems on-line smoothly while continuing to take on new projects. The potential for delays due to shortages in critical materials and engineering and skilled construction manpower was considered in their projections (Ref. 23).

The IGCI conducted a survey of 24 vendors (including nonmembers), asking for an assessment of each company's unconstrained capacity to provide commercial FGD systems. The IGCI analysis essentially assumed that each vendor polled would provide 100 percent of predicted capacity. This assumption may hold in the 1978-1980 period as more vendors gain experience and the most promising systems are licensed, but it is questionable for the 1974-1977 period because few vendors have proven capabilities to supply scrubbing systems. In addition, IGCI stated that possible material and labor shortages were not considered in their estimates (Ref. 30).

Figure I-4 shows the cumulative need and cumulative vendor capacity estimates made by SOCTAP and by IGCI in megawatts of installed capacity versus time. Also shown is the curve which the EPA hearing panel felt best estimates the ability of vendors to install FGD systems.

Because orders must be placed soon for scrubbers to be installed in 1976-1977, vendor capacity through that period is largely limited by existing experience and capability of vendors. For this reason, the panel felt that actual experience during this period will likely follow the more conservative SOCTAP estimate. Capacity in the later 1970's, however, will

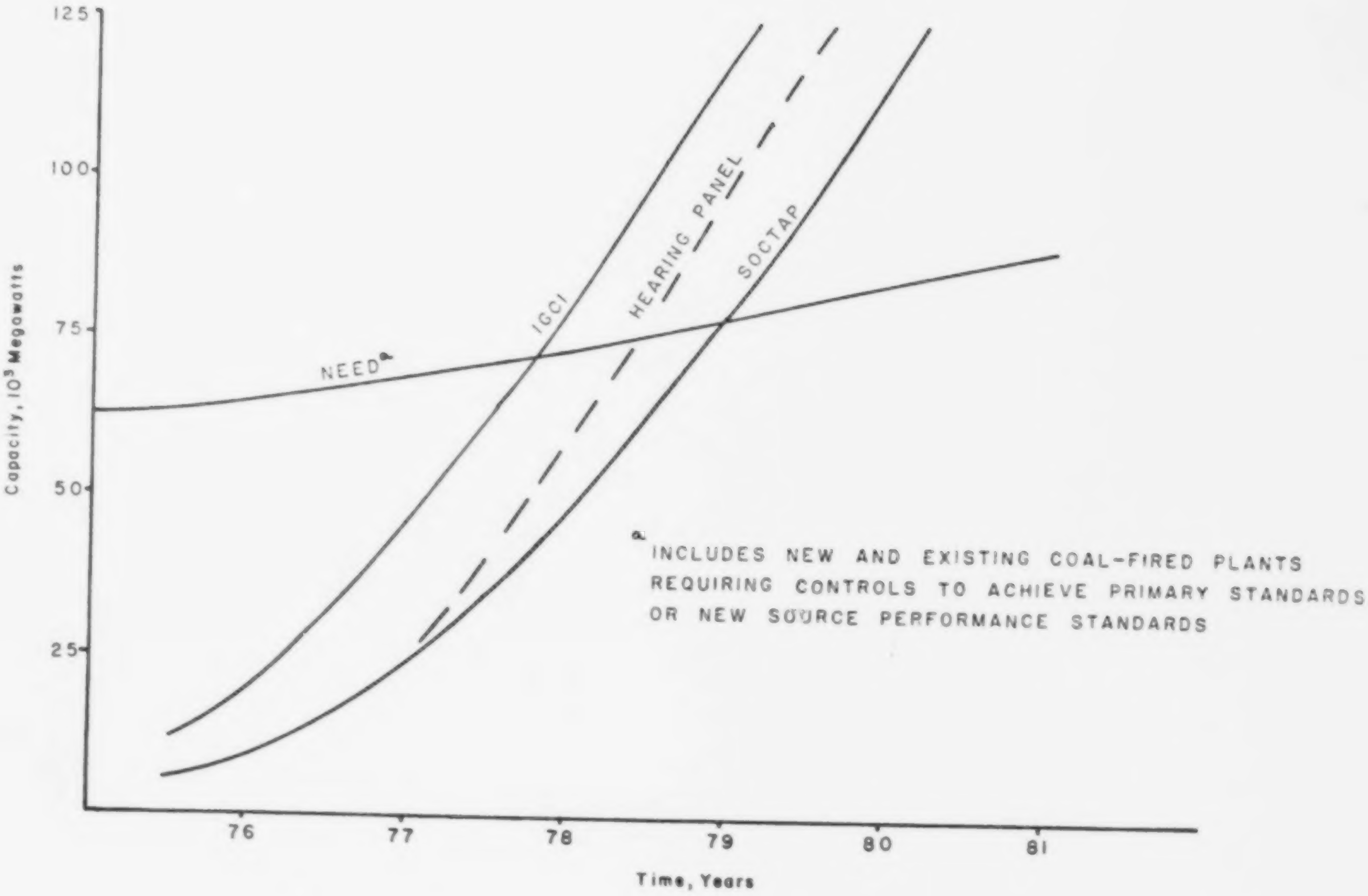


Figure I-4. Cumulative Need and Vendor Capacity.

depend on the extent to which additional vendors gain experience and the extent to which all vendors increase their capacities. This increase will depend largely upon the market the vendors envision. Assuming that states and EPA push ahead vigorously with sulfur oxide compliance requirements, the panel felt that actual experience during the later 1970's will most likely approach the IGCI estimates (Ref. 30).

Figure I-4 also shows EPA's best estimate of FGD needs (see Figure I-3) for existing coal-fired power plants impacting primary standards and for new coal-fired plants. On the basis of this estimate, it is clear that the timetables of many state implementation plans (compliance by mid-1975) will not be met. However, it is also clear that the vendor supply capability should be able to meet the demand for FGD systems by 1980.

In conclusion, during the 1974-1980 period, electric utilities will probably continue the current pattern in selecting wet scrubbing systems. The majority of orders will probably continue to be for lime/limestone scrubbing systems producing a throwaway sludge (Ref. 24). The balance of orders will be for regenerative systems, based on magnesium, sodium, and other compounds producing sulfur and sulfuric acid as by-products. The probable ratio of throwaway processes to regenerable processes indicated by current ordering trends is 3:1. It is felt that while the use of regenerable systems is expected to expand during the mid to latter part of the decade, the ratio of 3:1 will probably represent the cumulative population of systems in existence in 1980. Using the EPA estimate of FGD need of 90,000 Mw and this ratio results in 67,500 Mw projected to be controlled by lime/limestone scrubbing in 1980. However, since the EPA estimates exclude industrial boilers and oil-fired utility boilers, the lime/limestone demand alone could approach 90,000 Mw.

C. QUANTIFICATION OF THE PROBLEM AND COMPARISON WITH ANALOGOUS ENVIRONMENTAL PROBLEMS

One of the major problems inherent in any flue gas desulfurization system is the necessity to dispose of or utilize large quantities of sulfur removed from the flue gas. The sulfur compounds produced by flue gas desulfurization systems fall into two general categories: throwaway or salable products. Lime/limestone and double alkali scrubbing systems generate throwaway sludge products with little commercial value projected at the present time. Limestone scrubbing processes ordinarily produce sludges containing $CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$, and $CaCO_3$; lime sludges may also contain unreacted lime. For coal-fired installations where efficient particulate removal is not installed upstream of the wet lime/limestone absorber, such sludges can contain large quantities of coal ash. Even when efficient particulate collection is installed upstream of the scrubber, the disposal sludge may contain large quantities of ash.

A power plant SO_2 scrubbing system can be designed with the alternative of collecting fly ash simultaneously with the flue gas scrubbing operation or of collecting fly ash upstream of the scrubbing operation by precipitators and/or mechanical collectors. Additionally, the fly ash can be disposed of with the sludge or independently of it; and, in some cases, it can be used as an absorbent in the scrubber. The design decisions affect capital, operating and maintenance costs and could conceivably affect the operation of both the scrubber and boiler as well as disposal alternatives.

In the case of a retrofit scrubbing system, the preexistence of a particulate control system may determine the collection decision but not necessarily the disposal decision.

If a particulate collection system does not preexist, the installation of an SO_2 scrubbing system appears to be an inexpensive means of controlling particulate effluent at little additional cost.

In the case of a new plant, a decision to design without mechanical collectors and electrostatic precipitators will initially save their entire cost and would generally require little design change in the scrubbing equipment except for the differential required to handle a larger quantity of solids. Dependent on system design, the abrasive nature of fly ash could require additional replacement of scrubber system components incurring capital costs which would reduce the savings in initial capital expenditures. The difference in operational costs between the two methods of fly ash collection does not appear to be a primary consideration. These costs are highly dependent on the logistics of handling and disposal. However, maintenance costs for scrubber collected fly ash systems could be higher as a result of repair or replacement of hardware subjected to fly ash erosion. Unless properly designed, a base load unit without a separate particulate control system could find their compliance with particulate emission standards compromised during scrubber system outages. While variances for SO_2 emissions may be granted during these periods, it is not known whether, or to what extent, variances for particulate emissions would be granted. Some data suggest that a single scrubber can control SO_2 as well as particulates, that high alkaline ash may be used as a sorbent for SO_2, and that the erosive nature of the ash assists in controlling scaling and deposition. Additionally, the presence of ash in the sludge may enhance the settling characteristics of the combined waste thus requiring equivalent or even less disposal volume than the sum of the volumes required for separate sludge and ash disposal. Ash may also be required for disposal approaches incorporating chemical treatment (fixation).

The foregoing is intended only as a brief discussion of factors attendant to consideration of separate or combined collection, handling, and/or disposal of fly ash and sludge. A detailed discussion and analysis of these and other factors is beyond the scope of this report.

It appears that many utilities that have designed and installed lime/limestone scrubbing systems have not analyzed all the variables involved. At this point in time, probably due to lack of data, the utility companies have not indicated a consistent approach.

The following section will quantify projected scrubber sludge production and compare these quantities and related environmental considerations to those for wastes associated with a large utility unit and other industries and activities. Unless otherwise noted, quantities of sludge discussed in this report will be on a wet (50 percent solids) basis including coal ash.

1.0 Quantification of the Problem

The amount of sludge generated by a given plant is a function of the sulfur and ash content of the coal, the coal usage, the on-stream hours per year (load factor), the mole ratio of additive to SO_2, the SO_2 removal efficiency of the scrubbing system, the sulfite/sulfate ratio in the sludge, and the moisture content of the sludge. Table I-7 lists typical values of these various sludge parameters for a typical Eastern plant, a typical Western plant, and a hypothetical plant representing the national average expected between 1974 and 1980. The values listed as the national average represent a mix of Western and Eastern plants expected in 1980 based on the trends

Table 1-7. TYPICAL SLUDGE PRODUCTION PARAMETERS

Sludge Production Parameter	Large Eastern Plant	Large Western Plant	National Average
Coal:			
Sulfur Content, %	3.5	0.5-1.0	3.0
Ash Content, %	12	10	12
Plant:			
Load Factor, %	65-80	65-80	73
Coal Usage, Kg/Kwh	0.4	0.4	0.4
Scrubbing System:			
SO_2 Removal Efficiency, %	80-90	85-90	85
Moisture in Sludge, %	20-60	20-60	50
CaO/SO_2 (inlet), Mole Ratio	1.0-1.2	1.0-1.2	1.0
$CaCO_3/SO_2$ (inlet), Mole Ratio	1.2-1.5	1.2-1.5	1.2
Sulfite/Sulfate, Mole Ratio	9:1	9:1	9:1

shown by present flue gas desulfurization system orders. Table I-8 shows the effects of variations in the assumed values of these parameters.

The sulfur content of coal will vary from plant to plant. Comparison of Case 1 and Case 4 in Table I-8 shows that a 1000 Mw plant burning 3.5 percent S coal would have to dispose of as much as 908,000 metric tons/year (1,000,000 tons/year) more wet sludge than the same plant burning 0.7 percent S coal. The average coal fired in 1980 by controlled systems is expected to be about 3 percent.

The SO_2 removal efficiency will vary from one flue gas desulfurization system to the next as a function of local requirements. New Eastern plants will require 75-85 percent SO_2 removal to meet the new source performance standard of 2.2 $g/10^3$ kcal (1.2 lb $SO_2/10^6$ Btu). Existing sources are to be controlled in accordance with the provisions of the state implementation plans; for those Eastern systems requiring control to meet primary ambient air quality standards, SO_2 removal efficiencies required generally are in the 60-90 percent range. New Western plants require 0-50 percent SO_2 removal to meet new source standards; however, several Western states' implementation plans call for 50-175 ppm maximum effluent SO_2 concentration. Compliance with these implementation plans will require as much as 90 percent removal from Western plants. Comparison of Case 1 and Case 3 shows that lowering SO_2 removal from 90 percent to 80 percent could mean handling as much as 27,000 metric tons/year (30,000 tons/year) less sludge.

Since unreacted additive is disposed of with the sludge, the stoichiometry of lime or limestone addition (that is, the CaO/SO_2 or $CaCO_3/SO_2$ mole ratio) greatly influences

Table I-8. TYPICAL QUANTITIES OF ASH AND SLUDGE PRODUCED BY A 1000 MW COAL-FIRED GENERATING STATION CONTROLLED WITH LIME/LIMESTONE FLUE GAS DESULFURIZATION SYSTEMS, SHORT TONS PER YEAR [a]

	Case I Base Case	Case 2 Effect of Stoichiometry	Case 3 Effect of SO_2 Removal Efficiency	Case 4 Effect of Coal S	Case 5 1980 National Average
Coal ash, dry	338,000	338,000	338,000	282,000	338,000
Coal ash, wet (80% solids)	423,000	423,000	423,000	354,000	423,000
Limestone Sludge, dry					
$CaSO_3 \cdot 1/2H_2O$	322,000	322,000	286,000	64,000	261,000
$CaSO_4 \cdot 2H_2O$	48,000	48,000	42,000	10,000	39,000
$CaCO_3$ unreacted	185,000	92,000	216,000	37,000	92,000
Total	555,000	462,000	544,000	111,000	392,000
Limestone Sludge, wet (50% solids)	1,110,000	924,000	1,090,000	222,000	784,000
Limestone Sludge, wet (with ash, 50% solids)	1,790,000	1,600,000	1,760,000	786,000	1,460,000
Lime Sludge, dry					
$CaSO_3 \cdot 1/2H_2O$	322,000	322,000	286,000	64,000	261,000
$CaSO_4 \cdot 2H_2O$	48,000	48,000	42,000	10,000	39,000
CaO unreacted	52,000	17,000	69,000	11,000	22,000
Total	422,000	387,000	397,000	85,000	322,000
Lime Sludge, wet (50% solids)	844,000	774,000	794,000	170,000	644,000
Lime Sludge, wet (with ash, 50% solids)	1,520,000	1,450,000	1,470,000	734,000	1,320,000

[a] Assumptions:

Coal:	% S	3.5	3.5	3.5	0.7	3.0
	% ash	12	12	12	10	12
Plant:	hr/yr	6400	6400	6400	6400	6400
	lb coal/Kwh	0.88	0.88	0.88	0.88	0.88
Scrubber:	% SO_2 removal	90	90	80	90	85
	CaO/SO_2 mole ratio	1.2	1.0	1.2	1.2	1.0
	$CaCO_3/SO_2$ mole ratio	1.5	1.2	1.5	1.5	1.2
	% sulfite oxidation	10	10	10	10	10

the amount of sludge to be handled. Comparison of Case 1 and Case 2 shows that lowering the CaO/SO_2 mole ratio from 1.2 to 1.0 could lower the amount of sludge to be disposed of as much as 64,000 metric tons/year (70,000 tons/year). Lowering the $CaCO_3/SO_2$ mole ratio from 1.5 to 1.2 would result in 173,000 metric tons/year (190,000 tons/year) less sludge. The CaO/SO_2 and $CaCO_3/SO_2$ mole ratios vary from system to system at present, but the general trend is toward lower values as operating experience is gained. It is expected that reasonable values for this ratio in 1980 will be 1.0 and 1.2 for lime and limestone scrubbing, respectively.

Other factors influencing the amount of sludge to be handled are the load factor of the plant, the coal use rate, and the mole ratio of sulfite to sulfate in the sludge. The amount of sludge produced by a plant is directly proportional to the number of hours per year that the plant operates and the coal usage of the plant. The 6400 hr/year and 0.4 Kg/Kwh (0.88 lb coal/Kwh) values used for those calculations are typical of large modern generating stations (Ref. 31, 32). Obviously if the plant is on line a larger fraction of the year, the amount of sludge produced will increase. The sulfite to sulfate ratio in the sludge affects the weight of the sludge produced, as $CaSO_4 \cdot 2H_2O$ is heavier than $CaSO_3 \cdot \frac{1}{2}H_2O$. The ratio assumed in this report (9:1) is taken from the SOCTAP report (Ref. 23). However, some system designers are considering trying to completely oxidize the sludge to improve settling characteristics and decrease chemical oxygen demand. If this were done on a widespread basis, the weight of dry sludge produced per plant would increase but improved settling characteristics would tend to lower the proportion of water in the sludge.

Assuming the forecast demand for FGD control scrubbing previously discussed is accomplished entirely by lime/limestone scrubbing* and the national average annual sludge production rates per 1000 Mw of controlled generating capacity, the amount of wet ash-containing sludge (50 percent moisture) that will have to be disposed of annually by 1980 is predicted to be 119,000,000 metric tons of limestone sludge year (131,000,000 tons/year), or 108,000,000 metric tons of lime sludge/year (110,000,000 tons/year).

2.0 Comparison of Scrubber Sludge with Analogous Environmental Problems

To put sulfur oxide scrubber sludge into perspective with other wastes, two approaches were taken. The first was to view sludge as part of the land and solid waste impacts associated with a 1000 Mw coal-fired utility unit, thereby assessing intra-industry effects. The second was to compare sludge with wastes from other industries and activities, including some from the mining industry, for completeness.

As shown in Table I-9, the annual land and solid waste impact of a 1000 Mw coal-fired electric energy system equipped with flue gas desulfurization (FGD) for SO_x and particulate removal is 30,000-35,000 acres, depending on whether deep mining or surface mining of coal is used. The coal mining operations appear to have the greatest impact in terms of land

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*It is unlikely that all coal-fired utility FGD installations will be lime/limestone systems. However, the majority are expected to be, and other applications (e.g., oil-fired utility boilers, coal-fired industrial boilers) could make the projected sludge production figure quite realistic.

Table I-9 COMPARATIVE LAND AND SOLID WASTE IMPACT OF 1,000 MW ELECTRIC ENERGY SYSTEM (0.75 LOAD FACTOR)

(LOW LEVELS OF ENVIRONMENTAL CONTROLS EXCEPT FOR INSTALLATION OF A LIMESTONE FGD SYSTEM FOR SO_x AND PARTICULATE REMOVAL)

	Mining (Coal)[a]		Processing[a]	Transport[a]	Conversion[a] (Plant Site)	Limestone FGD System, Untreated Ponded Sludge[b]	Transmission[a]	Totals	
	Deep	Surface						Deep	Surface
Land Affected, acres[c]	9,120	14,010	161	2,213	350	367 (30 ft. depth)	17,188	29,399	34,289
Annual Solid Waste Produced, short tons	97,141 (wet, 97% solids) (101,346 with acid drainage sludge)	2,762,000 (wet, 98% solids) (2,762,328 with acid drainage sludge)	454,092 (wet, 99% solids)	zero	zero	1,460,000 (wet, 50% solids)	zero	2,011,233	4,676,092
Environmental Impact	1) Potential land degradation due to subsidence; 2) Acid mine drainage water pollution problems	1) Mined land made barren precluding wildlife habitat, recreation and most other uses; 2) Acid mine drainage water pollution problems	1) Culm piles; 2) Water pollution: a) acid drainage; b) siltation; 3) Air pollution: a) discharges SO_2, CO & H_2S; b) potential spontaneous combustion	Use of land for railroad beds	Use of land for power plant site	1) Potential groundwater pollution problems; 2) Land potentially made useless if sludge not treated or permanently dewatered	Use of land for transmission line right of way	N/A	N/A
Typical Technique(s) Available to Minimize Impact	1) No well developed cost-effective technology to control subsidence; 2) Neutralization of mine drainage with lime	1) Intensive land reclamation can restore most strip-mined land; 2) Neutralization of mine drainage with lime	Compacting in holes, mines, quarries, etc.	N/A	N/A	1) Although reclamation is feasible, no well developed, cost-effective technology has been demonstrated; 2) Sound pond management, use of impermeable pond liner, and operation of FGD system in closed-loop mode can minimize water pollution. (As an alternative to ponding, chemical fixation and landfill appears to have potential for solving both water pollution and land reclamation problems.)	N/A	N/A	N/A

[a] Ref. 33

[b] See Table I-8 (Case 5) for assumptions (also includes ash).

[c] Land affected is expressed as a time average of the amount of land in use over 30 years. Fixed land is taken at its full amount; average variables use (waste storage) is 15 times the annual incremental damage.

use and environmental effects. Although the right-of-way required for transmission lines actually consumes far more land than coal mining, this land is still available for other uses, public or private, and aside from aesthetics, the environmental effects are minimal. As transmission voltages get higher, however, the economics of larger more numerous conductors, grounding techniques, and transmission line height versus corona discharge and potential danger of induced shocks may result in the purchase and fencing of rights-of-way. This could take more land out of production than the right-of-way itself (Ref. 34).

A plant equipped with a lime/limestone FGD system for SO_x and particulate removal and using ponding for disposal will require just over two times as much total area as a plant site without SO_x or particulate control systems and about 1.5 times the total area of a plant with particulate control only and ash disposal by ponding. This increase in area (which may be at the plant site or at some remote location) is required for the disposal of the solid SO_x wastes generated by the FGD system.

Table I-9 also shows that large quantities of wastes are handled by coal mining and processing operations. It can be seen that an FGD system will produce quantities of solids roughly comparable to the mining operation (about three times greater than the deep mines, but about half that for strip mines).

Table I-10 presents a preliminary, semiquantitative comparison of most major U. S. solid wastes on an as-disposed-of basis. In addition to quantities of waste, typical compositions, disposal methods, potential environmental problems, and disposal costs are shown. Quantities are not directly

Table I-10. COMPARISON OF MAJOR SOLID WASTE DISPOSAL PROBLEMS

Waste Material	Quantity Disposed Annually in Referenced Year, metric tons, as disposed of	Composition	Method of Disposal	Land Use or Reclamation Considerations	Environmental Problems with Minimal Pollution Control	Estimated Disposal Costs, $/ton
Municipal and Industrial Refuse[a]	360,000,000[b] (1973) (75% solids)	40% municipal refuse, 60% industrial refuse Typical Composition: paper waste (64%); food waste (8%); glass and ceramic wastes (9%); garden waste (8%); rocks, dirt, etc. (4%); plastics, rubber, leather, textile, wood wastes (8%).	Landfills, incineration	Cover material needed to support vegetation	Undefined groundwater & surface water pollution; potential air pollution (incinerator emmissions, odor)	1-4 (landfill) 5-12 (incineration)
Culm Piles[c]	>91,000,000[d] (1969) (dry basis)	Waste coal, slate, carbonaceous & pyritic shales, clay, trace metals	Surface piles, landfills	Cover material required for plant growth. Provision for collection of drainage	Undefined water pollution; siltation; acid drainage; possible air pollution (odor); spontaneous combustion	0.30-0.50
Mineral Ore Wastes[e]	1,300,000,000[f] (1970) (dry basis)	Rock waste from mining operations	Surface piles, landfills	Needs cover material	Undefined groundwater & surface water pollution	<0.50
Coal Ash	95,000,000[g] (1980) (80% solids)	Solids Composition (wt %)[h] SiO_2 (30-50), Al_2O_3 (20-30), Fe_2O_3 (10-30), CaO (1.5-4.7), K_2O (1-3), MgO (0.5-1.1), Na_2O (0.4-1.5), TiO_2 (0.4-1.3), SO_3 (0.2-3.2), C (0.1-4.0), B (0.1-0.6), P (0.01-0.3), and trace metals	Ponding, landfills	Needs cover material	Undefined groundwater and surface water pollution	0.50-3.00 (exclusive of pond construction costs)
Limestone Scrubber Sludge (excluding coal ash)	64,000,000[i] (1980) (50% solids) (119,000,000 including ash)	Solids - generally mixtures of $CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$, and $CaCO_3$ Liquor - contains various amounts of dissolved species which originate in the coal, alkali, and makeup water	Ponding, landfills	Untreated sludge difficult to dewater	Potential groundwater & surface water pollution	2.50-4.50/wet ton (ponding) 2-10/wet ton (fixation and landfill)

Table 1-10 (Continued) COMPARISON OF MAJOR SOLID WASTE DISPOSAL PROBLEMS

Waste Material	Quantity Disposed Annually in Referenced Year, metric tons, as disposed of	Composition	Method of Disposal	Land Use or Reclamation Considerations	Environmental Problems with Minimal Pollution Control	Estimated Disposal Costs, $/ton
Municipal Sewage Sludge	55,000,000[b] (1980) (0.1-20% solids)	Composition of Raw, Primary Sludge, %:[j] Volatile matter - 60-80 Ash - 20-40 Insoluble ash - 17-35 Greases & fats - 7-35 Protein - 22-28 NH_4NO_3 - 1-3.5 P_2O_5 - 1-1.5 Cellulose - 10-13 Trace metals	Ponding, landfills	Hard to dewater, difficult to develop	Undefined ground-water & surface water pollution; potential air pollution	0.50-10
Phosphate Rock Slime[k]	760,000,000[f] (1970) (4-6% solids)	Solids Composition (wt %)[l] P_2O_5 (9-17), Al_2O_3 (6-18), SiO_2 (31-46), CaO (14-23), Fe_2O_3 (3-7), MgO (1-2), CO_2 (0-1), F (0-1), BPL (19-37), LOI (9-16), trace metals	Ponding	Hard to dewater (settles to only 30% solids after years). Not established that dried solids will support vegetative growth.	Undefined ground-water & surface water pollution	0.03-0.05
Acid Mine Drainage Sludge[m]	8,200,000[n] (1973) (1-5% solids)	Typical Solids Composition (wt %)[o] $CaSO_4$ (40), MgO (1), $MgSO_4$ (5), Fe_2O_3 (15), CaO (3), Mn_2O_3 (4), SiO_2 (20), Al_2O_3 (12), trace metals	Ponding	Hard to dewater	Undefined ground-water & surface water pollution	0.04-0.25
Gypsum From Fertilizer Manufacture[k]	28,000,000[p] (1973) (85-90% solids)	Chiefly $CaSO_4 \cdot 2H_2O$	Ponding, surface piles	Needs cover material to support vegetation & make aesthetically acceptable	Undefined ground-water & surface water pollution	--

Table 1-10 (Continued) COMPARISON OF MAJOR SOLID WASTE DISPOSAL PROBLEMS

Waste Material	Quantity Disposed Annually in Referenced Year metric tons, as disposed of	Composition	Method of Disposal	Land Use or Reclamation Considerations	Environmental Problems with Minimal Pollution Control	Estimated Disposal Costs $/ton
Taconite Tailings	1,100,000,000[q] (1971) (4-5% solids)	Typical Solids Composition (%):[r] Fe - 17 Si - 33 Al - 0.35 Ca - 1.67 Mg - 2.55 Mn - 0.37 Ti - 0.030 P - 0.026 Na - 0.20 K - 0.06 S - 0.03 C - 0.11 H - 0.10 O - 46.40 Trace elements	Ponding, lake dumping (Reserve Mining Co.)	Fertilization, mulching, etc. required for reclamation of ponds	Potential ground and surface water pollution	0.005-0.05 (lake dumping)

[a] Exclusive of agricultural and mining wastes.

[b] Ref. 35.

[c] Bituminous coal only.

[d] Ref. 36.

[e] Mining wastes from metal and non-metallic ores, exclusive of fossil fuels; no processing wastes included.

[f] Ref. 37.

[g] Assumptions: 12% ash, 6400 hr/yr, 248,000 Mw installed coal-fired generating capacity (1980), 0.4 kg coal/Kwh.

[h] Ref. 38.

[i] Assumptions: 3% S, 12% ash, 6400 hr/yr, 90,000 Mw controlled generating capacity, 85% SO_2 removal, 0.4 kg coal/Kwh, 1.2 $CaCO_3/SO_2$ (inlet) mole ratio, 10% oxidation.

[j] Ref. 39.

[k] 80% disposed of in Florida.

[l] Ref. 40.

[m] Most acid mine drainage comes from abandoned mines and receives no treatment.

[n] Ref. 41

[o] Ref. 42.

[p] Ref. 43.

[q] Assumptions: >100 million tons crude taconite ore annually, 25% average iron content, 60% beneficiation.

[r] Ref. 44.

comparable since they are based on many different sources and time periods.

Considering the quantities of wastes disposed of on a wet or as-disposed-of basis, of those wastes surveyed in Table I-10, several are generated in significantly greater amounts than projected 1980 scrubber sludge. Both mineral ore wastes and taconite tailings production rates are approximately an order of magnitude greater than the projected sludge production rate, while phosphate slimes and municipal/industrial refuse also greatly exceed sludge in amounts generated. Culm pile material and projected coal ash from utilities without FGD systems are generated in amounts slightly greater than projected sludge, while sewage sludge, gypsum from phosphate fertilizer manufacture, and acid mine drainage sludge production quantities are less than that of projected scrubber sludge.

As is the case for scrubber sludge, ponding and landfilling provide the major mechanisms of disposal for most waste products. In terms of land use and reclamation, and potential surface water and groundwater pollution, these disposal mechanisms have many points of similarity for the various industries. In some cases, land use for waste disposal has destroyed wildlife habitat and is aesthetically objectionable. In addition, all wastes have the potential for providing varying degrees of surface and groundwater pollution depending on their chemical compositions and solubilities, and the location, design, and operation of the disposal site. With proper site selection and design (possibly including a permanent impermeable liner) and sound operating practices, however, surface water and groundwater pollution can be avoided.

For land reclamation, most of the stable wastes will require only a cover material to support growth of vegetation and to prevent eventual erosion of wastes by run-off water. However, some wastes (phosphate rock slime, sewage sludge, untreated scrubber sludges) are very resistant to dewatering and could reslurry in the pond or landfill. In some cases, these disposal sites could become only a temporary storage site which could present a deferred disposal problem as well as a difficult land reclamation problem. Fixation technology, now commercially available and applied at several full-scale installations, appears to be a successful approach to land reclamation. In Florida reclamation of slime ponds has been successfully achieved using tailings from the flotation process to aid in dewatering. Another type of approach to the potential land use problem is based on production of a sludge more amenable to landfill disposal by an oxidation process.

Costs for waste disposal vary greatly depending on the treatment and transportation of the wastes. Disposal costs are minimal for phosphate rock slime and similar wastes which typically are not treated, are disposed of near the plant site, and have little land reclamation activity. The projected cost range for disposal of scrubber sludge is broad. The low end represents no treatment and on-site disposal in an unlined pond. The high end represents steps to solve both the land reclamation and water pollution problems by chemical treatment and transportation to an off-site landfill. Discharge of scrubber sludge to a lined pond solves the water pollution problem only, and based on available data, cost would be, as a minimum, $0.50/wet ton and could be considerably higher.

In summary, based on preliminary comparisons of available information on quantities, compositions, and current disposal methods, untreated scrubber sludge disposal may produce an environmental impact somewhat analogous to those associated with other solid wastes such as culm piles, municipal sewage, municipal industrial refuse, and coal ash. Significant quantities of scrubber sludge are projected for 1980, but waste disposal problems of similar and larger magnitudes have been dealt with by industry for many years. Although the total environmental impact associated with disposal of untreated scrubber sludge in a soil-lined disposal area is not well-defined, currently available technology has the potential for environmentally acceptable disposal. Furthermore, solutions to achieve satisfactory disposal will be influenced by emerging environmental restrictions. Research efforts to thoroughly evaluate potential hazards and available technology is continuing through government-funded contractors, utilities, and fixation technology vendors.

D. RELATIONSHIP BETWEEN SULFUR OXIDE SCRUBBER SLUDGE, STANDARDS/REGULATIONS, AND ENFORCEMENT

In this section, the relationship between sludge and current or proposed federal pollution laws and standards and their implementation and enforcement will be discussed for each medium--air, water, and solid waste

1.0 Air

Pursuant to the Clean Air Act as amended in 1970, the Environmental Protection Agency promulgated National Primary and Secondary Ambient Air Quality Standards (NAAQS) and New Source Performance Standards (NSPS) in April and December of 1971, respectively. NAAQS for sulfur dioxide and other pollutants apply to all areas of the nation. Resulting state implementation plans restrict SO_2 emissions from significant sources. Since fossil fuel-fired power plants are large SO_2 emitters, most implementation plans limit emissions from these sources to at least some degree. NSPS apply to new fossil fuel-fired steam generators larger than about 25 megawatts capacity.

Analysis by EPA's Office of Air and Waste Management (OAWM) indicates that the principal areas of the country affected by SO_2 from steam generators lie within EPA Regions III, IV, and V and Four Corners Air Quality Control Region (AQCR). Regions III, IV, and V consumed about 84 percent of the coal used in 1971 and contain the largest number of AQCR's rated Priority I and IA for SO_2. These priorities are indicative of the highest ambient air concentrations. It is important to note that about half of the coal estimated to be used in 1975 will be burned in these Priority I and IA AQCR's. Regions III, IV, and V also include those states that produce most of the high-sulfur coal in the country. Most of the states have found or will find it necessary to issue regulations limiting SO_2 emissions from steam generators. In many cases, flue gas desulfurization (FGD) will be necessary to achieve emission levels consistent with primary and secondary ambient air quality standards. Current schedules require that activities resulting in FGD system installation be initiated already or within the next few years.

Since the subject of FGD systems is vital to the aims of the Clean Air Act of 1970, EPA initiated national hearings which extended from October 18 through November 2, 1973. Testimony was offered by utilities as well as vendors of FGD systems and sludge handling processes, fuel suppliers, state, local, and federal officials, and other interested parties. The hearing panel found that sulfur oxide scrubbing technology was generally available but that the utility industry considers the disposal of solid waste (sludge) generated by the throwaway class of FGD systems to be a major problem. Two potential environmental problems associated with uncontrolled sludge disposal were mentioned: water pollution and land deterioration. However, during the course of the hearings, technology was described which has the potential for minimizing or eliminating these problems. This technology includes closed-loop operation, use of pond liners, and chemical treatment (fixation) enabling disposal of an acceptable landfill material.

The panel believes that a large number of appropriate landfill sites are available for sludge disposal. There are specific applications, generally in urban areas, where sludge disposal could be expensive due to lack of readily available landfill sites. The panel recommends that regenerable or salable product FGD systems which do not produce throwaway sludges or fuel switching be considered for these applications.

2.0 Water

Two areas of concern have been addressed in two major pieces of legislation dealing with water quality--surface water and groundwater. The Federal Water Pollution Control Act (FWPCA) Amendments of 1972 strongly address surface waters, while the Safe Drinking Water Act of 1974 is directed toward preservation of groundwater quality.

The objective of the FWPCA Amendments, enacted October 1972, is the restoration and maintenance of the chemical, physical and biological integrity of the Nation's waters. With the national goal that the discharge of pollutants into navigable waters be eliminated by 1985, the act requires the EPA Administrator to:

1. Develop and keep updated criteria for water quality (including groundwater), accurately reflecting the latest knowledge and information related to effects on health and welfare from the presence of pollutants, as well as the factors necessary for restoration and maintenance.

2. Develop guidelines for effluent limitations for point sources, other than publicly owned treatment works, to be met July 1, 1977, using best practicable technology currently available.

3. Develop guidelines for effluent limitations for point sources, other than publicly owned treatment works, to be met July 1, 1983, using best available technology economically achievable.

4. Develop and keep updated guidelines for identifying and evaluating the nature and extent of nonpoint sources of pollutants and processes, methods, etc. to control pollution.

5. Develop standards of performance, including zero discharge, where practicable, for pollutant effluent from new point sources, other than publicly owned treatment works, using best available demonstrated control technology.

6. Develop more stringent limitations, if necessary, to meet water quality standards.

7. Develop and keep updated effluent standards for toxic pollutants or combinations of such pollutants.

A number of requirements relate to effluents from point sources. In the case of a power plant with a lime/limestone scrubbing flue gas desulfurization system, this would influence the extent of scrubber liquor bleed. Completely closed-loop operation, which is most desirable for FGD system economics as well as avoiding water pollution problems, would have no bleed per se. Liquor would leave the system by only two means--water evaporative losses in the scrubber and that liquor associated with the sludge. In addition, a number of requirements relate to water quality (including groundwater) from nonpoint sources such as ponds and landfills.

The FWPCA Amendments appear to encompass any pollutant discharge with the potential for degrading water quality directly through seepage, discharge, or runoff, or indirectly through groundwater contamination.

The Safe Drinking Water Act of 1974 further emphasizes the need for protection of groundwater supplies. The Act requires all states to develop effective underground-water protection programs utilizing money, manpower, and guidance from the federal government.

To meet the responsibilities of these pieces of legislation, additional information characterizing chemical and physical properties of FGD sludge and associated liquors is desirable. Also, treatment techniques and cost effective and environmentally acceptable disposal require further definition. Programs which are planned and underway will provide this necessary information.

3.0 Solid Waste

There are currently a number of solid waste bills before Congress that might affect the handling of lime/limestone scrubber sludge. When enacted, the provisions would be carried out by the Office of Solid Waste Management Programs (OSWMP).

The impact of the enacted Federal Water Pollution Control Amendments (FWPCA) of 1972 and the proposed solid waste management acts cannot be fully evaluated at this time. However, the implementation of both acts requires EPA to issue guidelines and limitations regarding water discharge and waste disposal. These guidelines will be issued and periodically updated on the basis of best available control technology. Additional information concerning chemical and physical characteristics of the flue gas desulfurization system liquors and sludge, and of their potential handling and disposal techniques, will ensure responsible implementation of this legislation.

E. NATURE OF THE MATERIAL

The environmental effects of sludge disposal will be dictated by the chemical and physical properties of the material; these properties may vary widely for different operations. Important variables include the sulfur and ash content of the coal, the type of scrubber operation (lime or limestone) and amount of excess material added, the amount of ash in the sludge, the type of limestone, type of recycle (closed loop, open loop, or partially closed loop), and the degree of oxidation of the sulfite. Several studies are currently underway to quantify the influence of these variables. At the present time it is not possible to give an analysis which truly represents all systems. Those data which are available are summarized in the following discussion.

It should be noted that only recently has a significant amount of effort been expended in characterizing sludge materials. The information presented in this section should be considered preliminary in nature until additional test data are available.

Chemical characteristics of sludge are related to potential water pollution problems, while physical characteristics influence the land use aspects of disposal such as land degradation and potential reclamation of disposal sites. Chemical and physical characteristics of the sludge will be discussed separately in this section of the report.

1.0 Chemical Properties of Sludge and Related Materials

The potential water pollution problems derived from the chemical properties of the sludge can be broken down into the following categories:

1. Soluble trace metals.
2. Chemical oxygen demand.
3. Excessive total dissolved solids.
4. Excessive levels of other major species, e.g., sulfate, chloride, calcium, and magnesium.
5. Excessive suspended solids (some of which might dissolve later).

Some data have already been generated which help to put these potential problems in perspective. The great majority of these data have been generated in laboratory studies, pilot plants, or large units which do not have a lengthy record of continuous operation. It is expected, therefore, that the results strongly indicate those that would be obtained by a large system in continuous operation, but may not be exactly the same. In addition, almost every system is unique in terms of the coal, lime or limestone, and scrubber system parameters; therefore, current results should best be interpreted as trends.

Scrubber sludge solids consist mainly of calcium sulfite hemihydrate ($CaSO_3 \cdot \frac{1}{2}H_2O$), calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), calcium carbonate ($CaCO_3$), and fly ash. Table I-11 shows quantities of these major components in several SO_2 scrubber sludges from specific FGD installations, and also points up the variability in composition of sludges from different operations. Another source gives a typical composition for sludge as shown in Table I-12.

Trace elements occurring in sludge may originate either in the coal, the lime or limestone, or the makeup water; however, coal is generally regarded as the primary source. A particular element may ultimately be found in the fly ash, bottom ash, flue gas, or in the plant's discharge. Because coal ash and scrubber sludge represent similar disposal problems, and because they are often discarded together, it is desirable to know the chemical composition of each waste stream for assessing their water pollution potential.

Typical ash components are silica, alumina, and hematite; also present are various amounts of minor and trace elements, some of which are considered toxic. Data in Table I-13 illustrate typical compositions of power plant coal ashes. The uranium and thorium values represent Eastern coals only;

Table I-11. CHARACTERISTICS OF SLUDGE FROM OPERATING SO_2 SCRUBBERS[a]

Facility	Rate (dry basis), metric tons/hr	Sludge Composition (dry basis), wt percent				Estimated Solids Content of Dewatered Sludge, wt percent
		$CaSO_3 \cdot 1/2H_2O$	$CaSO_4 \cdot 2H_2O$	$CaCO_3$	Fly Ash	
Lawrence 4	10.7	10	40	5	45	50
Lawrence 5	34.4	10	40	5	45	50
Hawthorn 3	12.4	20	25	5	50	40
Hawthorn 4	15.4	17	23	15	45	40
Will County 1	17.5[b]	50	15	20	51	35
Stock Island	2.4	20	5	74	1[c]	50
La Cygne	12.5	40	15	30	15	35
Cholla	3.1	15	20	0	65	50
Paddy's Run 6	5.3	94	2	0	4	40
Mohave 2	1.5[b]	2	95	0	3	65

[a] Ref. 45

[b] Prior to stabilization

[c] Mainly unburned carbon

Table I-12. CHEMICAL COMPOSITION OF TYPICAL DESULFURIZATION SYSTEM SLUDGE[a]

Fly Ash	17-20%
$CaSO_3 \cdot 1/2H_2O$	65%
$CaSO_4 \cdot 2H_2O$	5-7%
$CaCO_3$	3%
Others	3-5%

[a] Ref. 46

Table I-13. POWER PLANT COAL ASH COMPOSITIONS[a]

Constituent	% By Weight
Silica (SiO_2)	30-50
Alumina (Al_2O_3)	20-30
Ferric Oxide (Fe_2O_3)	10-30
Lime (CaO)	1.5-4.7
Potassium Oxide (K_2O)	1.0-3.0
Magnesia (MgO)	0.5-1.1
Sodium Oxide (Na_2O)	0.4-1.5
Titanium Dioxide (TiO_2)	0.4-1.3
Sulfur Trioxide (SO_3)	0.2-3.2
Carbon (C) and volatiles	0.1-4.0
Boron (B)	0.1-0.6
Phosphorus (P)	0.01-0.3
Uranium (U) and Thorium (Th)	0.0-0.1

[a] Ref. 38

none were readily available for Western coals. Table I-14 shows the results of analyses of trace elements in two coal samples, a fly ash sample, and a bottom ash sample. The ash samples are from a Western coal containing 10 percent ash. The differences between the Eastern coal and the Western coal are notable. Relative to the Western coal, the Eastern coal is very high in zinc, manganese, barium, chromium, and vanadium. The Western coal is higher in arsenic, antimony, selenium, and nickel. It is also important to note that the fly ash from both coals is generally higher in trace element content than the bottom ash.

The ultimate fate of a given species in the solid waste (ash and/or sludge) will be determined largely by its solubility. The major components of sludge have limited solubilities, while fly ash is even less soluble. Generally, 2-5 percent of fly ash is water-soluble. The resulting solution is usually alkaline due to the effect of free lime (CaO) although some ashes, especially from Eastern coals, produce acidic sluice waters. The principal soluble species are calcium and sulfate ions, with limited amounts of sodium, magnesium, potassium, and silicate also present. Table I-15 contains analyses of ash leachate from a plant burning acidic coal and sparse information on ash leachate from a plant fired with alkaline coal.

Other types of data for predicting potential impact on water quality due to simultaneous ash/sludge disposal are analyses of ash ponds. Ponded fly ash solids from progressive sampling points through the ash disposal system at the Oak Ridge Y-12 steam plant were collected. The analyses are presented in Table I-16. These results may be used to examine the dissolution/precipitation of a given species with time. It appears that the concentration of most of the elements in the solids remains relatively stable.

Table I-14. SELECTED TRACE ELEMENTS IN COALS AND ASH[a]

Element	Composition, PPM			
	Eastern Coal	Western Coal Composite Sample	Samples from Western Coal-Fired Plant	
			Fly Ash	Bottom Ash
Arsenic	N.D.[b]	3	15	3
Mercury	<0.01	0.05	0.03	<0.01
Antimony	<0.05	0.17	2.1	0.26
Selenium	N.D.	1.6	18	1
Cadmium	N.D.	<0.5	<0.5	<0.5
Zinc	180	0.56	70	25
Manganese	350	15	150	150
Boron	46	15	300	70
Barium	1800	400	5000	1500
Beryllium	<0.01	N.D.	3	<2
Nickel	N.D.	25	70	15
Chromium	310	5	150	70
Lead	30	4	30	20
Vanadium	180	9	150	70

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[a] Ref. 47

[b] N.D. - Not detected.

Table I-15. ASH LEACHATE COMPOSITIONS FROM POWER PLANTS BURNING ACIDIC AND ALKALINE COAL^{a,b}

	Power Plant Using Acidic Coal							Power Plants Using Alkaline Coal					
	Actual Discharges From the Fly Ash Disposal Site			Bottom Ash In Pond	Fly Ash From Three Different Silos			Plant #1		Plant #2		Plant #3	
								Fly Ash	Bottom Ash	Fly Ash	Bottom Ash	Bottom Ash	Fly Ash
Parameter	L-26	L-27	L-28	L-29	L-30	L-31	L-32	L-33	L-34	L-35	L-36	L-37	L-33
pH	2.7^{b}	2.75 ^{b}	2.5^{b}	5.35	4.35	4.0	4.4						
TDS													
Alkalinity	3460	2440	4240			[illegible]80	82						
Sulfate (SO_4)	5167^{b}	3915^{b}	4982 ^{b}	80.75	777 ^{b}	2006^{b}	464 ^{b}	1620^{b}	18	1260^{b}	150	42	1500 ^{b}
Total Iron (Fe)	815 ^{b}	352.5^{b}	697.5^{b}	0.08	0.30	2.90^{b}	0.10	<0.05	0.15	<0.05	<0.05	<0.05	< 0.05
Copper (Cu)	0.05	0.07	0.19	<0.01	1.37 ^{b}	6.75^{b}	1.04 ^{b}						
Zinc (Zn)	4.25 ^{b}	3.63^{b}	5.13 ^{b}	2.0^{b}	18.25^{b}	22.75^{b}	16.75^{b}						
Chromium (Cr)													
Lead (Pb)	0.30 ^{b}	0.30^{b}	< 0.10	<0.10	< 0.10	0.3^{b}	< 0.10						
Cadmium (Cd)	0.03 ^{b}	0.03^{b}	0.04 ^{b}	0.09^{b}	0.09 ^{b}	0.15^{b}	0.03 ^{b}						
Mercury (Hg)													
Manganese (Mn)	152.5	142.5^{b}	85^{b}	0.33	1.09 ^{b}	2.15^{b}	0.64 ^{b}						
Arsenic (As)								<0.01	< 0.01	<0.01	<0.01	< 0.01	< 0.01

[a] Ref. 48

[b] Exceeds stream criteria

Table I-16. ANALYSES OF DRY FLY ASH SOLIDS FROM THE Y-12 STEAM PLANT[a,b]

Element	Composition, Wt Percent[c]		
	Sample A	Sample B	Sample C
Aluminum	>20	20	18
Barium	0.12	0.12	0.10
Boron	0.03	0.05	0.05
Calcium	0.6	0.6	0.6
Chromium	0.03	0.03	0.03
Copper	0.02	0.03	0.03
Iron	10	10	7
Lead	0.01	<0.01	<0.01
Lithium	0.04	0.08	0.08
Magnesium	0.6	1.0	0.9
Manganese	0.04	0.04	0.08
Nickel	0.02	0.03	0.03
Potassium	-	3	2.5
Silicon	20	35	30
Sodium	0.6	0.7	0.6
Titanium	0.3	1.0	0.8
Vanadium	0.03	0.04	0.08

[a] Ref. 49

[b] These samples are from the Oak Ridge Y-12 steam plant. Sample A was collected at the overflow from the primary retention basin to a water filled quarry which acts as a settling pond. Sample B was collected at the outfall of the quarry, and Sample C was collected where the overflow enters a lagoon of a lake.

[c] Compositions determined by spectrographic methods. All other elements present in quantities less than their detectable limits.

Table I-17 characterizes the ash pond discharge from TVA's Widows Creek Station over a period of 1 year. Trace element composition of an unidentified ash pond is compared to Public Health Service (PHS) Drinking Water Standards in Table 1-18. Manganese and selenium exceeded the limits for this particular sample.

A minor portion of trace elements may also be introduced into the sludge with the lime or limestone and makeup water. Several analyses of different limestone additives are given in Tables I-19 through I-22.

The final distribution of the trace elements in the solid and liquid phases can be useful in predicting whether a water pollution problem exists, either from the pond effluent or from landfill leachate. Table I-19 presents analyses of metals and other trace species for the solids collected at various points in TVA's limestone scrubbing system at Shawnee. Concentrations of these species in samples of coal and limestone used in the system are also shown. In Table I-20 the relative amounts of metals in the clarifier solids are compared with those in the liquid associated with the solids from the same scrubber operating in partially closed loop. As might be expected, sodium, potassium, magnesium, and calcium are soluble. In addition, such species as boron, molybdenum, manganese, silicon, and copper also occur at significantly higher levels in the liquid. Other trace metal species are concentrated in the solids. It should be noted that equilibrium may or may not have been reached; i.e., given time, additional solids might dissolve.

The concentrations of various species in the solids and liquid effluents from a centrifuge can be compared in

Table I-17. CHEMICAL ANALYSES OF ASH POND DISCHARGE FROM TVA'S WIDOWS CREEK[a]

Sample Identity	pH	Concentration, ppm										
		Total Solids	Total Dissolved Solids	Alkalinity, Total $CaCO_3$	Total Hardness, $CaCO_3$	Ca	Mg	SO_4	Cl	SiO_2	Fe	Mn
1971 Quarterly Samples, TVA's Widows Creek	7.3	250	240	34	69	20	4.6	100	21	5.4	0.29	0.44
	9.0	190	190	45	99	34	3.4	95	11	4.4	0.42	0.02
	9.8	210	210	61	130	47	3.7	70	19	6.1	0.27	<0.01
	9.1	210	210	75	130	45	4.3	60	17	5.6	0.69	0.02

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[a] Ref. 50

Table I-18. SELECTED ELEMENTS IN SOLUTION[a,b]

Element	Concentration, ppm		
	Ash Pond Liquor	Scrubber Liquor (Aerospace Data)	PHS Drinking Water Standard
Lead	0.01	<0.01	0.05
Antimony	0.015	N.D.[c]	
Barium	0.07	<0.05	1
Manganese	0.075	1.6	0.05
Mercury	<0.001	N.D.	
Beryllium	0.002	N.D.	
Boron	0.5	11	
Nickel	0.015	0.05	
Cadmium	0.01	N.D.	0.01
Selenium	0.035	N.D.	0.01
Zinc	0.03	N.D.	5
Arsenic	0.01	N.D.	0.05

[a] Ref. 47

[b] The ash pond data represent approximate levels which might normally occur. The scrubber liquor is analysis of an unspecified sludge liquor.

[c] N.D. - Not detected.

Table I-19. SPARK SOURCE MASS SPECTROGRAPHIC ANALYSIS OF SCRUBBER SOLIDS[a]

	Concentration, ppm							
							Fly Ash	
Element	Coal	Limestone	TCA Effluent Separated Solids[b,c,d]	TCA Effluent Slurry Solids[b,c]	Clarifier Solids[b]	Bottom Ash	TCA Inlet	TCA Outlet
Li	3.3	1.8	5.1	7.9	1.2	42	6.5	13
B	46	1.5	28	42	7.6	220	38	220
C	(>1%)	4,900	1,700	170	140	2,500	2,000	7,000
N	30	4.5	1	3	3	3	5.1	230
F	7.9	12	30	16	5.9	4.1	4.2	30
Na	1,700	360	2,800	290	270	350	870	2,800
Mg	1,700	(>1%)	(>1%)	(>1%)	(>1%)	9.700	4,400	5.700
Al	7,500	4,200	(>1%)	(>1%)	(>1%)	(>1%)	--	--
P	40	85	170	150	110	680	140	1,800
S	(>1%)	220	(>1%)	2,100	330	200	440	1,200
Cl	280	38	47	79	42	17	25	58
K	3,000	580	3,700	760	860	1,300	960	2,500
Ti	5,900	440	4,500	5,300	4,200	(>1%)	6,000	(>1%)
V	180	15	94	150	150	290	65	820
Cr	310	76	240	250	66	700	440	230
Mn	350	140	180	230	190	530	180	290
Fe	4,500	2,500	(>1%)	(>1%)	(>1%)	(>1%)	--	--
Cu	N.D.[e]	N.D.	33	49	N.D.	220	25	140
Zn	180	59	330	450	90	640	290	1,600
As	N.D.	N.D.	24	53	16	3	22	450
Rb	24	1.7	13	30	9.0	63	11	40
Sr	1,100	1,500	750	1,500	1,100	170	400	1,300
Y	95	N.D.	63	45	27	340	73	47
Cs	N.D.	N.D.	1	1.2	N.D.	6.0	1.3	1.4
Ba	1,800	10	1,600	870	520	(>1%)	1,000	6,400
Pb	30	N.D.	20	64	N.D.	N.D.	27	64
Br	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	6.5	N.D.

[a] Ref. 51

[b] Sample for Columns 4, 5, and 6 were centrifuged and dried at Aerospace.

[c] Samples for Columns 4 and 5 were obtained upstream of the clarifier.

[d] Column 4 sample was filtered at the scrubber site.

[e] N.D. - Not detected.

Table I-20. EMISSION SPECTROGRAPHIC ANALYSES OF LIMESTONE AND CLARIFIER LIQUOR AND SOLIDS[a]

Species[b]	Distilled Water, ppm	Clarifier Liquor, ppm	Clarifier Solids, Wt %	Limestone, Wt %
Ca	TR[c] < 0.004	1100.	27.	35.
Mg	0.0040	67.	1.4	2.9
Si	0.085	14.	8.9	0.65
B	0.018	11.	0.0092	N.D. < 0.005
Mn	N.D.[d] < 0.01	1.6	0.013	0.011
Fe	0.055	0.17	0.25	0.10
Al	< 0.04	0.34	2.6	0.012
Mo	< 0.02	0.56	Nil	Nil
Cu	0.0064	0.0017	0.00053	0.00011
Na	N.D. < 1.0	TR < 7.5	0.23	0.036
Ni	0.058	0.05	0.0017	N.D. < 0.001
Sr	N.D. < 0.01	2.1	0.099	0.078
K	N.D. < 2.0	19.	0.88	N.D. < 0.20
Co	Nil	Nil	TR < 0.001	N.D. < 0.001
Cr	Nil	Nil	0.0025	0.00084
Ti	Nil	Nil	0.53	N.D. < 0.003
Pb	Nil	Nil	0.015	N.D. < 0.01
Ca	Nil	Nil	0.0027	N.D. < 0.002
Other Cations	Nil	Nil	Nil	Nil

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[a] Ref. 51.

[b] Balance is sulfate, sulfite, oxides, and carbonates.

[c] TR - Trace

[d] N.D. - Not detected

Table I-21. These data are from a limestone turbulent contact absorber (TCA) scrubber pilot plant; the fuel was a Western coal. It can be seen that many metals are concentrated in the liquid phase, including iron, aluminum, magnesium, sodium, boron, titanium, manganese, chromium, copper, and nickel. The pH of this liquid is not known, but a low pH might account for the high metal solubility. In Table I-22 the relative content of metals in the limestone versus the centrifuged solids can be compared for this same pilot plant. These data were obtained employing a different analytical technique. Table I-23 shows some typical sludge liquor compositions and compares them to EPA proposed water quality criteria. The concentrations of arsenic, cadmium, chromium, mercury, boron, chloride, and sulfate exceed the limits in at least one case. Other sources have reported other elements such as cadmium, selenium, nickel, and magnesium to be in excess of various water standards. Sulfate, chloride, and total dissolved solids are often in excess of the limits.

Chlorides and trace metals which are volatilized and/or form ultrafine particulates during coal combustion are collected in the scrubber. This indicates the multipollutant control potential of FGD systems. Approximately 95 percent of the chloride in the coal has been found to be evolved as HCl in the combustion gases (Ref. 53). Oak Ridge National Laboratory found that electrostatic precipitators were efficient for most elements contained in the fly ash. However, mercury, selenium, and possibly arsenic, were noted as exceptions. Approximately 90 percent of the mercury in the coal was estimated to be unaffected by the precipitator (Ref. 54).

The effect of pH on trace metal solubility is currently under investigation. Preliminary results from an Aerospace

Table I-21. EMISSION SPECTROGRAPHIC ANALYSIS OF SOLIDS FROM A WESTERN STATION[a]

Element	Composition, Wt %					
	Scrubber Input From Holding Tank	Scrubber Output To Holding Tank	Centrifuged Solids	Centrate	Make-Up Water	Limestone
Si	10.	1.6	1.4	18.	22.	0.24
Ca	25.	35.	37.	4.2	9.6	39.
Fe	1.2	0.29	0.18	3.6	4.2	0.070
Al	3.4	0.90	0.79	15.	6.2	0.0099
Mg	0.53	0.18	0.20	1.3	1.4	0.30
Na	2.4	1.6	0.69	5.2	TR < 0.20	TR < 0.06
Ba	N.D.[b] [c]< 0.20	---	---	0.19	TR < 0.20	N.D. < 0.20
B	TR < 0.005	0.0063	TR < 0.005	0.016	0.017	N.D. < 0.005
P	N.D. < 0.50	---	---	TR < 0.50	2.6	N.D. < 0.50
Ti	0.10	0.056	0.044	0.94	0.12	N.D. < 0.004
Mn	0.017	0.0076	0.0055	0.046	0.13	0.025
K	TR < 0.40	TR < 0.40	---	0.94	N.D. < 0.40	---
Fb	TR < 0.02	0.016	TR < 0.01	0.064	0.034	N.D. < 0.01
Ga	N.D. < 0.006	---	---	0.024	TR > 0.006	N.D. < 0.006
Cr	0.0071	0.0070	0.0042	0.072	0.038	0.0014
Mo	N.D. < 0.004	---	---	0.0088	N.D. > 0.004	---
Sn	N.D. < 0.008	---	---	---	TR > 0.008	N.D. < 0.008
V	N.D. < 0.008	---	---	0.030	N.D. > 0.008	---
Cu	0.0041	0.0025	0.00089	0.036	0.38	0.00022
Zn	N.D. < 0.06	---	---	---	0.86	N.D. < 0.06
Ni	0.0024	0.0041	0.0029	0.014	0.0028	N.D. < 0.002
Co	N.D. < 0.002	---	---	0.0043	TR < 0.002	N.D. < 0.002
Sr	0.030	0.11	0.14	0.095	0.16	0.039
Other	Nil	---	---	---	---	---

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[a] Ref. 51.
[b] N.D. - None detected.
[c] TR - Trace

Table I-22. SPARK SOURCE MASS SPECTROMETRY ANALYSIS OF SOLIDS FROM A WESTERN STATION[a]

	Composition, ppm			
Element	Detection Limit	Scrubber Output to Holding Tank	Centrifuged Solids	Limestone
Li	0.07	7.9	5.5	0.31
B	0.1	28	35	0.80
C	0.1	920	5,500	
N	1	72	41	2.2
P	0.1	190	3,500	4.3
Na	0.07			1,700
Mg	0.7	7,400	5,600	4,000
Al	0.5			3,300
P	0.2	1,100	390	50
S	2			30
Cl	0.5	1,600	1,400	4.3
K	0.1	1,100	2,100	330
Ti	1	1,100	3,700	160
V	0.5	42	59	5.3
Cr	0.7	250	290	19
Mn	0.5	90	180	150
Fe	1			900
Cu	1	1	1	N.D.[b]
Zn	1	71	210	6.0
As	1	58	46	11
Rb	0.7	22	7.3	0.7
Sr	3	1,700	1,600	220
Cs	3	53	N.D.[b]	N.D.[b]
Ba	5	1,400	2,000	N.D.[b]

[a] Ref. 51

[b] N.D. - Not detected.

Table I-23. CHEMICAL ANALYSIS OF SLUDGE LIQUORS[a,b]

Element	Scrubber. Size, Mw Percent Solids in Discharge	TVA Shawnee Lime	TVA Shawnee Limestone	SCE Mohave Limestone	Plant B Lime (Eastern coal)	Water Quality Criteria EPA Proposed Public Water Supply Intake Oct 1973
		Concentration, ppm				
	Size, Mw	10	10	1	100	
	Percent Solids in Discharge	50-55	35-40	75-80	35-40[c]	
Calcium		2520	1600	1400	1400	--
Magnesium		25	600	-[d]	410	--
Boron		40.8	-[d]	-[d]	-[d]	1.0
Chloride		5000	2500	30,000	2700	250
Fluoride		3.3	3.4	3.1	2.6	--
Sulfate		800	2000	2500	2250	250
Sulfite		0.9	110	0.1	20	--
TDS[e]		9000	7000	70,000	7000	NO LIMIT[f]
Arsenic		0.02	0.02	0.03	0.085	0.1
Beryllium		0.002	0.01	0.001	0.012	--
Cadmium		0.10	0.005	0.05	0.023	0.01
Chromium (total)		0.03	0.15	0.005	0.040	0.05
Copper		0.002	0.02	0.08	0.048	1.0
Lead		0.5	0.1	0.01	0.18	0.05
Mercury		0.001	0.06	0.0012	0.045	0.002
Selenium		0.02	0.30	0.12	0.80	0.01
Zinc		0.08	0.30	0.12	0.09	5.0
pH		9	8	7	9	5 to 9

[a] Ref. 52.

[b] All sludge liquor samples, except those from SCE Mohave, contain significant amounts of fly ash.

[c] An undetermined amount of clarifier overflow liquor is discharged from this system, making the effective percent solids in discharge somewhat lower than value shown.

[d] To be determined.

[e] Includes other soluble species (e.g., sodium and potassium).

[f] "No Limit" indicates that insufficient data existed for prescribing limits.

Corporation study indicate that the least environmental hazard exists at an alkaline pH under reducing conditions. The further suggest that there is no set of chemical conditions for untreated sludge which will eliminate all of the hazards due to trace metal solubility (Ref. 51). Soil attenuation mechanisms will likely reduce the potential hazards and are currently under study.

Total dissolved solids (TDS) in scrubber liquors and from ash liquors vary widely. Data for TDS are given in Tables I-17 and I-23. The sludge liquor from TVA's Shawnee lime scrubbing system was reported to have 7000 ppm TDS in the sludge liquor. The limestone system at SCE's Mohave Station which operates in a very tight closed loop system reported 70,000 ppm TDS. Ash liquor data from Ohio Valley power plants indicate an average TDS value of 750 ppm (Ref. 38). Widows Creek ash liquor data indicate an average of about 230 ppm. The higher TDS values of sludge liquors include calcium and magnesium compounds, chlorides, and some trace elements. The fact that sludge does contain significant quantities of soluble material necessitates careful disposal of untreated material to avoid environmental problems in terms of surface or groundwater contamination.

In summary the data indicate:

1. The solid phase of scrubber sludge will consist essentially of the calcium compounds noted above (See Page 77). These calcium compounts have a limited solubility in sludge liquors. The major components of fly ash are even less soluble.

2. Scrubber sludge and ash solids will contain trace elements originating in the coal. Based on data available at this time, the major source of heavy metal concentrations in sludge is the coal. Trace elements and other species may also originate in the limestone or lime, the make-up water, and ash sluice water, but their contribution to the total trace element content of the sludge is minor.

3. Sludge and ash liquors will contain dissolved species from the solid constituents in accordance with solubilities which are generally an inverse function of pH. The chemistry of the coal, particularly chlorine and sulfur content, and the type of scrubber system employed will determine the pH of the untreated sludge liquors.

4. Liquors associated with scrubber sludge may also contain species such as chlorides and certain trace metals which are volatilized during coal combustion and removed in the scrubber. These species are generally unaffected by dry ash collection techniques so they are emitted to the atmosphere and not found in the ash liquor. This indicates the multipollutant control potential of FGD systems.

5. Limited data indicate total dissolved solids (TDS) vary widely in sludge liquors and ash liquors. Levels for scrubber sludge liquors tend to be considerably higher, in some cases by an order of magnitude or more. These higher TDS values include calcium compounds, magnesium compounds, trace elements, and chlorides.

2.0 Physical Properties and Settling Characteristics of Scrubber Sludges

As for the chemical properties, physical properties of sludge may vary widely, and may be influenced by many factors in a manner that is not yet well understood. It should be noted that these results are preliminary and may or may not be typical of large-scale continuous operations.

The physical properties are important in terms of sludge disposal since they have an influence on the difficulty of handling, transporting, treating, and ultimately disposing of the material. Physical properties also are important in regard to land reclamation of abandoned disposal sites.

The areas of potential concern here are:

1. Rewatering of the dried, aged material.
2. Strength, i.e., load bearing capacity.
3. Ability to support vegetation growth (chemical properties are also important here).

Particle size measurements have been reported for a number of sludge compositions (Ref. 55, 56). Both wet screen and subsieve analytical techniques were utilized. The results are presented in Tables I-24, I-25, and I-26. Identification of most of the samples analyzed is included in Table I-24. The results indicate that the particle sizes fall in the range of silt with minor percentages in the fine sand and clay size proportions.

A related parameter, the Blaine index, is a measure of the total surface area of dry solids. The Blaine index for a packed bed of material was determined by measuring the permeability by ASTM method C204-55. The Blaine index was then determined by its inverse relationship to the permeability. These results are presented in Table I-27.

Permeabilities of settled and freely drained sludge were reported by Aerospace to be $2.2 - 2.3 \times 10^{-4}$ cm/sec (depending on column heights). These values are roughly equivalent to those of fly ash (Ref. 52). Sulfate sludges have higher permeabilities than sulfite sludges when both are in settled states. Drainability (a property which is directly related to permeability) of both types of sludges, especially sulfate sludges, is reduced by up to two orders of magnitude by compaction and addition of fly ash.

The bulk density of various scrubber sludges varies as a function of water content. As the percent of water increases from zero, the bulk density increases as the pore volume becomes filled. When completely filled, a maximum bulk density is reached. With greater percentages of water, a dilution effect is observed as the bulk density decreases. For Shawnee (limestone sludge with fly ash) clarifier underflow

Table I-24. WET SIEVE ANALYSIS OF SCRUBBER SLUDGES [a]

Mesh	Cumulative Wt % Retained				
	+40	+100	+200	+325	+400
Fly Ash	0.2	1.7	7.1	15.1	--
Eastern Coal Lime Sludge[b]	--	--	--	7.5	13.5
Western Coal Lime Sludge[c]	--	--	--	--	1.0
Dry Injected/with Wet Scrubber Sludge[d]	--	--	--	--	29.2
Limestone Scrubber Sludge[e]	--	--	--	--	18.4
Smelter Gas Sludge[f]	--	--	--	--	2.4
Unidentified FGD Sludge	--	1.1	4.9	9.3	14.3

[a] Ref. 55, 56.

[b] Lime scrubbing sludge from a power plant burning Eastern Coal; ash present.

[c] Lime scrubbing sludge from a power plant burning Western Coal; no ash present.

[d] Sludge produced by limestone injected into the boiler followed by wet scrubbing; ash present.

[e] Limestone scrubbing sludge from a pilot plant burning oil; no ash.

[f] Lime scrubbing sludge from molybdenum sulfide smelter; no ash present.

Table I-25. SUBSIEVE ANALYSIS OF FLY ASH AND AN EASTERN COAL LIME SCRUBBER SLUDGE[a]

Micron	Cumulative Wt % Retained	
	Fly Ash	Eastern Coal Sludge
+50	15	1
+40	--	2
+30	--	5
+20	27	12
+17	32	--
+15	--	21
+10	47	39
+ 7	62	51
+ 5	--	68
+ 2	92	88
+ 1	97	--

[a] Ref. 26

Table I-26. SUBSIEVE ANALYSIS[a]

Equivalent Spherical Diameter, microns	Cumulative Wt %
+18	10
-18	90
-12	80
- 9	70
- 8	60
-6.4	50
- 5	40
- 4	30
- 3	20
-1.5	10

Blaine Fineness Number 7600

[a] Source: Micromerities Instrument Corp. as cited in Ref. 56.

Table I-27. BLAINE INDICES FOR SCRUBBER SLUDGES[a]

Sample (refer to Table I-24)	Blaine Index (cm^2/g)
Fly Ash	2,640
Eastern Coal Sludge	12,500
Western Coal Sludge	27,500
Dry Injected/Wet Scrubber Sludge	14,100
Limestone Scrubbing Sludge	11,100
Smelter Gas Sludge	3,670

[a] Ref. 55

samples, the peak bulk density was reported to be 1.7 g/cm^3 (106 lb/ft^3) at 70 percent solids content. The bulk density of a packed and dried Shawnee sample was 1.2 g/cm^3 (75 lb/ft^3). These data are compared to the true density of Shawnee solids equal to 2.5 g/cm^3 (155 lb/ft^3) (Ref. 51). Practical dewatering methods do not remove sufficient water to obtain maximum bulk densities in the Shawnee sludge. In comparison, the sludge from the Mohave power plant also employing a limestone system was shown to have a maximum bulk density of 1.87 g/cm^3 (117 lb/ft^3) at 78 percent solids content. The Mohave scrubber sludge has a true density of 2.53 g/cm^3 and a bulk density of 1.46 g/cm^3. For this sludge, maximum bulk densities can be achieved by dewatering (Ref. 51). Based on measurements for several sludges, Lord reported that typical values for bulk density of settled sludge range from 1.4 - 1.5 g/cm^3 (85 - 95 lb/ft^3) (Ref. 56). Specific gravities of the dry sludge solids ranged from 2.48 to 2.55.

Typical packing volumes for settled fly ash, sulfate-based sludge, and sulfite-type sludge were reported to be 0.6, 1.4 and 2.3 m^3 per metric ton (20, 45 and 75 ft^3 per ton) (Ref. 45). Sulfite sludges will require greater storage volumes because sulfites tend to crystallize in small, thin platelets that settle to a loose bulky structure, occluding a relatively large amount of water.

Viscosity measurements for Shawnee limestone scrubber sludges and limestone scrubber sludges from Mohave have also been reported (Ref. 51). The Shawnee samples, 50 - 60 percent solids, exhibited a viscosity which decreased with stirring time. This was due to the thixotropic nature of the sulfite-laden material. If the stirrer was shut off for 1 minute, however, the viscosity returned to a higher value, which then decreased with time. The viscosity measurements ranged from 120 to 20 poise (cf. water, 0.01 poise). The shear rate was reported to be 7.9 cm/sec (15.6 ft/min) at 64 rpm.

The limestone scrubber sludge from the Mohave power plant displayed markedly different properties due to its high clay content. In fact, the sludge settled so rapidly and was so viscous that measurements were limited to those less than 50 poise. Some of the especially stiff mixtures (>65 percent solids) displayed sporadic rheopectic behavior; i.e., increase of viscosity with stirring time (Ref. 51).

TVA has determined the gel strength of a 16 percent solids sludge from a limestone system employing a torsion wire gelometer (Ref. 57). This parameter was found to be a strong function of time as indicated by the data in Table I-28.

Table I-28. GEL STRENGTHS OF A LIMESTONE SYSTEM SLUDGE

Time After Stirring	Strength (g x cm)
0	0
30 min.	6
18 hr.	>25

Shrinkage of untreated, dried Shawnee sludge was reported to be a function of water content. The degree of linear shrinkage for a molded, air-dried sample was reported to be 3.7 percent (Ref. 51).

Compaction strength is measured by the resistance of wet sludge to penetration of a flat bottom ram, 1.0 cm diameter, pushed in at the rate of 1.27 cm/min. This parameter is used to evaluate the mechanical stability and load-bearing capacity of ponded sludge. This property is a strong function of water content. Results for Shawnee and Mohave sludges are presented in Figure I-5. Shawnee sludge at 45 percent moisture was judged to lack any appreciable degree of compaction strength; however, if dried to 30 percent water content, it showed a substantial increase in strength to 21,000 - 25,000 kg/m^2 (30 - 35 psi) (Ref. 51). The stress required to support a person is ~2000 kg/m (3 psi), which is achieved by Shawnee sludge at approximately 61 percent solids. Safe access for personnel can probably be granted if the solids content is greater than 65 percent, at which point the load-bearing strength is expected to be 5600 kg/m^2 (8 psi). Vacuum filtration can dewater Shawnee sludge to this extent. Reduction of moisture content to 30 percent or less will probably be necessary before the sludge can support the weight of vehicles.

Bearing strength for Mohave sludge does not vary smoothly as a function of water content. At 65 percent solids a sharp increase in compaction strength occurs, ranging from 2100 to 21,000 kg/m^2 (3 to 30 psi). Mohave sludge can be dewatered to this point by any of the dewatering processes, including settling. At 65 percent solids, ponded Mohave sludge is probably safe for equipment and personnel.

Pozzolanic strength determinations were made by applying compression strength at a constant strain rate to ash-containing samples which had been cast in cylindrical molds and cured for a given time in a humid environment. Initial uncured strength was determined on samples unmolded after 5 days.

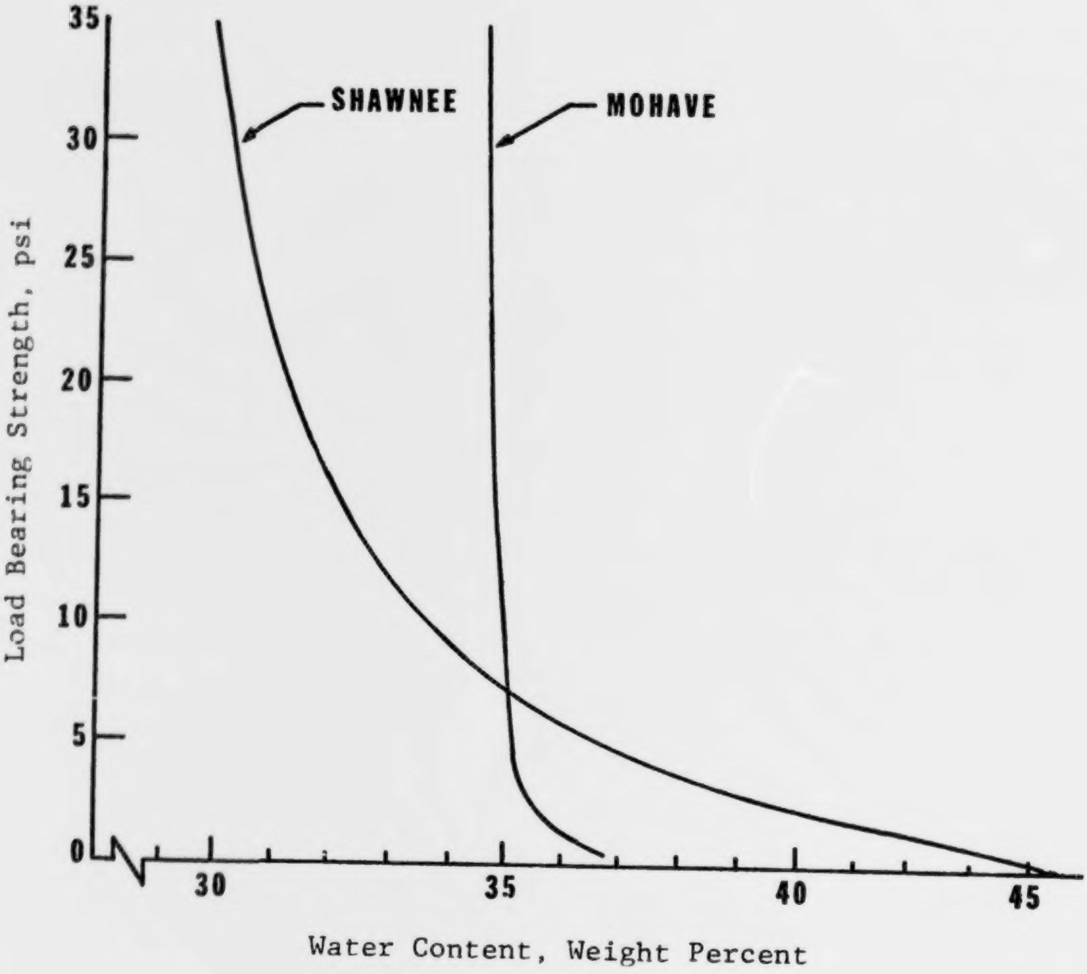

Figure I-5. Sludge Compaction Strength
(Ref. 51).

Additional testing was done at 1-month intervals. This property reportedly varied as a function of water content. Testing was carried out with an Instron test machine using a cross-head speed of 0.05 cm/min. Shawnee sludge samples showed negligible compressive strength. Loads of less than 2.3 kg (5 pounds), equivalent to strengths of 18,000 kg/m^2 (26 psi), were the limits even after 4 months of curing. Mohave sludge samples withstood greater loads when damp (freshly demolded) than when cured for longer periods. Uncured samples had strengths of 1.2 x 10^5 kg/m^2 (170 psi) and cured, dried samples measured 7.0 x 10^5 kg/m^2 (100 psi).

Direct shear testing was performed by Dravo on unstabilized FGD sludges to compare effects of stabilization. The untreated sludge exhibited an angle of internal friction between 27 and 30^o (Ref. 56). Strengths were found comparable to that of medium dense sand.

The thixotropic nature of sludge with high sulfite content poses some difficulty with respect to load-bearing properties. Dewatered Shawnee sludge (50 percent solids) was placed in an open-air, drained pit 2.4 x 2.4 x 0.3 meters and allowed to dewater naturally for 30 days. At the end of this time the solids content was 36 percent solids and the sludge appeared firm; large cracks were evident on the surface. A load of 2400 kg/m^2 (500 lb/ft^2) (minimum for recreational purposes) was placed on a 1.2 meter (4 foot) square section of surface. After 10 days no settling had occurred. However, the solids fluidized and lost all bearing strength when vibrated with a concrete vibrator (Ref. 58).

Due to the nature of scrubber wastes produced by lime/limestone systems, settling is not expected to result in extensive separations. From a bench-scale experiment conducted by TVA, a settling rate of 5 cm/hr (12.7 in./hr) was observed for the first and second phases of settling, which were defined as the induction period during which floc formation occurs and the second stage, free settling (Ref. 57). The third phase is compression settling; i.e., when the flocs begin to touch each other and gel formation occurs. The settling rate during this stage was greatly reduced. After 48 hours the settling rate decreased to practically zero and no further settling was observed, even over a period of several months.

Aerospace reported that limestone sludges with high sulfate content settle to 45 percent solids with no drainage provided. This is compared to final settled solids content of 50 percent with underdrainage. Sludges with high sulfite content were found to settle only to 35 percent solids regardless of whether drainage was provided (Ref. 51). The presence of fly ash will generally improve settling of high sulfite sludges (cf. 30 - 35 percent for low fly ash and 35 - 40 percent solids for high fly ash) (Ref. 59). For specific sludges, Shawnee samples settled to 45 percent solids and drained freely to 52 percent; Mohave sludge, a high sulfate type, reached 67 percent solids regardless of whether drainage was provided. Percentages of sulfite oxidation for the two samples were reported to be 20 - 25 percent and 75 percent, respectively (Ref. 51). In investigating the effects of underdrainage on the drainage rate in bench-scale column studies, the steady-state drainage rate for wet Shawnee sludge was reported to be 0.046 cm^3/min. When sludge was allowed to air dry in the columns, several days were required for initiation of drainage again; the drainage rate was then much less than that observed for wet sludge. Eventually, enough water was retained by the sludge column to return it to its original water content (51.7 percent).

Dravo Corporation compared solid contents of various power plant waste after one day of settling. Identities of samples for which data are presented below were given in Table I-24 (Ref. 55).

Sludge Source	Wt Percent Solids
Eastern Coal Sludge (with ash)	<30-45
Western Coal Sludge (no ash)	21.5
Dry Injected/Wet Scrubber Sludge (with ash)	24
Limestone Scrubbing Sludge (no ash)	39
Smelter Gas Sludge (no ash)	37-40
Fly Ash	64

Figure I-6 presents results of a settling test for an FGD sludge, presumably from an Eastern coal-fired, lime scrubbed utility. The sample tested contained 35 grams of solids per liter. These results indicate that essentially all of the settling occurs within the first 60 minutes with little further settling afterwards (Ref. 56, 60).

Settling characteristics of lime/limestone scrubbing sludges are directly related to the degree of compaction. The factors affecting this parameter include the following, all of which are under investigation by TVA (Ref. 57):

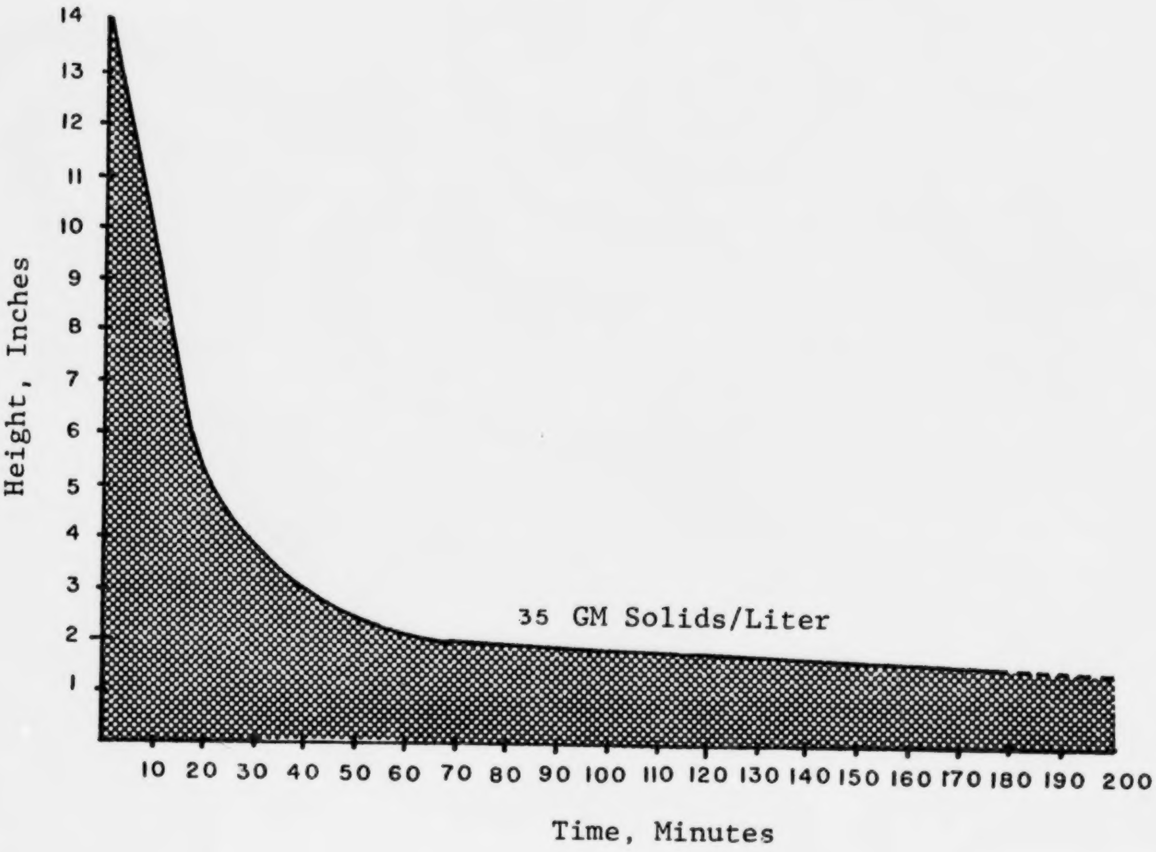

Figure I-6. Settling Test for Untreated FGD Sludge (Ref. 56).

1. Hydraulic head.

2. Ash content.

3. Degree of oxidation (percentage of $CaSO_4 \cdot 2H_2O$).

4. Stirring.

5. Agglomeration.

6. Lime versus limestone.

Results of bench-scale studies indicate that increasing the height of the slurry column increases degree of compaction. When the height of an experimental column was increased from 13 cm to 100 cm (5.1 to 39.4 inches) compaction was increased by 15 percent.

The influence of ash content on settling characteristics of scrubber sludge is not completely characterized. However, it is predicted that a high ash content in the sludge would improve settling although no data are available to support this point. This type of information could bear on the decision to dispose of scrubber sludge and fly ash together or separately.

Degree of oxidation is under intensive study. It is known that calcium sulfate (gypsum) crystals, because of their large blocky nature, settle better than the thin plate-like calcium sulfite hemihydrate crystals. Thus, oxidation to sulfate should improve the degree of compaction. It has been reported that a high degree of oxidation is required, however, to produce a noticeable effect. Methods under study to promote oxidation of limestone scrubber slurries include:

1. Air introduction into the scrubber.
2. Oxidation in separate unit; e.g., scrubber effluent hold tank.
3. Spinning cup oxidizer.
4. Use of catalysts.

Technology developed in Japan involves the use of a spinning cup oxidizer (rotary atomizer) treating low pH (3.5 - 4.0) slurry and is considered to be a commercially demonstrated process to produce a high quality gypsum product (Ref. 61, 62). Another oxidation process applied involves catalytic oxidation of the sulfite and SO_2 by further contact with flue gas and air. The catalyst is recycled by precipitation as the hydroxide.

Identification of scrubber conditions which promote agglomeration of sulfite crystals has not been made yet. Some sulfite crystal agglomeration has been noted. Flocculating agents are being investigated to determine their effectiveness in promoting appreciable agglomeration. The type of limestone and the particle size may also influence settling characteristics of the sludge.

An interesting general observation reported by Crowe was that sludges composed entirely of either calcium sulfite, fly ash, or calcium carbonate dewater readily and are relatively stable after dewatering (Ref. 58). However, mixtures of these three types exhibit poor dewatering and compaction qualities. It was suggested that the calcium carbonate somehow contributes to the poor settling characteristics of some sludges.

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II. APPROACHES TO DISPOSING OF OR UTILIZING SCRUBBER SLUDGE MATERIALS

Several alternatives are available for disposition of waste material generated by lime/limestone scrubbers. They include commercial utilization, ponding of untreated sludge, and landfilling of treated and untreated material. Other possibilities which have not received much attention thus far are deep mine disposal and deep well injection.

Ponding and landfilling are the chief methods used by the utility industry to dispose of ash from fuel combustion. Most technology available to date is based on experience with that material. Technology associated specifically with sludge is just now being demonstrated. The following sections discuss commercial utilization, describe various features of each disposal operation and, on the basis of available data, present the potential impact on water pollution and land use.

A. COMMERCIAL UTILIZATION

1.0 Overview

Considerable research has been performed to determine the technical properties and characteristics of the potential commercial products of sludge. As a result, numerous products and applications have been developed, some of which would require the consumption of a major portion of the available sludge if used on a large scale on a national basis. However, to do so would require that these new products successfully compete both technically and economically on the open market with well established manufactured or natural products. With sludge being a relatively new material not yet available in large quantities throughout the nation, a true test of the market has not been made. However, indications are that the potential sludge products will not compete well enough in the near term to consume an appreciable portion of the projected supply and that the principal concern for sludge will be disposal and not utilization.

2.0 Technical State-of-the-Art

2.1 Potential Utilization

Research, development, and investigative activities have been conducted concerning the potential utilization of power plant desulfurization sludges by numerous government and private organizations. Some of the more significant of these include the EPA (Refs. 1, 2, 3), the Bureau of Mines (Ref. 4), the Federal Highway Administration (Ref. 5), West Virginia University's Coal Research Bureau (Refs. 1, 2, 6), the TVA (Ref. 7), the Aerospace Corporation (Ref. 3), Combustion Engineering, Inc. (Ref. 8), I.U. Conversion Systems, Inc. (Refs. 9-12), the National Ash Association (Ref. 13), and Dravo Corporation (Ref. 14). These efforts have identified sludge as a unique raw material which has some potential use in the manufacture of products now using fly ash as an additive, or in new products or applications.

An inspection of the listing of products for which fly ash is used as an additive, and the applicability of the sludges to these products, provides an insight into the great difficulty attached to the possible utilization of the throwaway sludge. For example, an annual survey conducted by the Edison Electric Institute (Ref. 13) presents a breakdown of ash collection and utilization in the United States for the year 1971. This breakdown is given in Table II-1. Several significant factors relevant to sludge utilization can be derived from the chart and previous EEI surveys (Ref. 3); (1) a low percentage of the available fly ash actually used; (2) some technical capability but an economic inability to apply sludge in most uses of fly ash; and (3) the economic inability to apply sludge in the major use of bottom ash and boiler slag; e.g., fill material for roads.

In Table II-1, it is shown that 5 percent of all fly ash produced was utilized in the products noted, and that another 6.7 percent was removed from plant sites at no cost to the utility (some was used and the remainder was probably stored). In addition, there is the utilization of bottom ash and boiler slag, principally as a constructional fill material with which the sludges cannot compete economically because the bottom ash and slag are used as aggregate without appreciable processing while sludge must be chemically treated (fixed) before it can be used for this purpose. When all these applications for power plant ash are considered, the maximum utilization is about 20 percent of the total quantity produced. Of these applications, the "stabilizer for road bases, parking areas, etc." category is the only current use in which the sludge should be able to compete in the ash market from a technical and economic standpoint. As an artificial aggregate, it can also enter some local markets depending on the supply of natural aggregate. However, the current ash-usage categories of "road bases" and "aggregate" account for a usage of less than 1 percent of the total ash produced. Also, it has been shown that for a given power plant, an alkali scrubber system will produce a sludge (including ash, dry basis) quantity approximately twice the quantity of the ash produced without scrubbing (Ref. 15). Therefore, with the by-product production increased as much as 2 times at a given plant, and the potential utilization in the near term being inconsequential

Table II-1. ASH COLLECTION AND UTILIZATION YEAR 1971[a]

	Fly Ash Tons	Bottom Ash Tons	Boiler Slag (if Separated from Bottom Ash) Tons
1. Ash utilized			
a. Mixed with raw material before forming cement clinker	104,222	-	91,975
b. Mixed with cement clinker or mixed with cement (pozzolan cement)	16,536	-	-
c. Partial replacement of cement in:			
1. Concrete products	177,166	35,377	76,563
2. Structural concrete	185,467	-	-
3. Dams and other mass concrete	71,411	-	-
d. Lightweight aggregate	178,895	13,942	-
e. Fill material for roads, construction sites, etc.	363,385	533,682	2,628,885
f. Stabilizer for road bases, parking areas, etc.	36,939	7,880	49,564
g. Filler in asphalt mix	147,655	2,833	81,700
h. Miscellaneous	98,802	475,417	428,026
Total Item 1	1,380,478	1,069,131	3,356,713
2. Ash removed from plant site at no cost to utility but not covered in categories listed under Item 1.	1,872,728	542,895	381,775
3. Total ash utilized	3,253,206	1,612,026	3,738,488
4. Ash removed to disposal areas at company expense	24,497,848	8,446,941	1,232,298
5. Total ash collected	27,751,054	10,058,967	4,970,786
6. Estimated 1976 ash production	36,994,436	117,411,603	2,517,703

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[a] Ref. 13

on a national basis, the disposal of the by-product appears to be the principal method for handling these materials.

2.2 Effect of Material Properties

Chemical analyses of various sludges are presented in Table II-2. The compositions can be seen to vary widely with such things as the sulfur and ash contents of the coal burned and the methods of SO_2 and particulate collection. As a result, the physical properties also vary from sludge to sludge. Not only are the variations in properties great, but the differences when compared to regular fly ash are considerable.

The principal problems that face the utilization of the sludge are, therefore, centered in several areas: (1) the quality of the sludge is affected appreciably by the sulfur content of the coal burned, and by the efficiency of the combustion and scrubbing process; (2) the sludge contains sulfur which creates additional problems of sulfur gas evolution for manufacturing processes employing high temperatures; (3) the pozzolanic (concreting) properties of the sludge are weak when compared to those of fly ash; and (4) the volume of sludge produced will be much greater than that of the ash produced without the scrubbing process.

On the positive side, as appropriate, the sludge contains: (1) some pozzolanic properties, (2) nominal amounts of unreacted alkali, and (3) appreciable amounts of gypsum.

Another point to consider is the collection of fly ash in the scrubber. At power plants where efficient fly ash collection systems exist, the fly ash is collected upstream of the scrubber. In those cases, very little fly ash exists in the sludge and, for essentially all developments for sludge

Table II-2. CHARACTERISTICS OF SLUDGE FROM OPERATING SO_2 SCRUBBERS[a]

Facility	Nominal Sulfur Content of Coal wt percent	Nominal Ash Content of Coal wt percent	Method of Particulate Control	Method of SO_2 Control	Rate (dry basis), metric tons/hr	Sludge Composition (dry basis), wt percent				Estimated Solids Content of Dewatered Sludg wt percent
						$CaSO_3 \cdot 1/2H_2O$	$CaSO_4 \cdot 2H_2O$	$CaCO_3$	Fly Ash	
Lawrence 4	3.8	12	Marble bed	Limestone injection	10.7	10	40	5	45	50
Lawrence 5	3.8	12	Marble bed	Limestone injection	34.4	10	40	5	45	50
Hawthorn 3	3.0	13	Marble bed	Limestone injection	12.4	20	25	5	50	40
Hawthorn 4	3.0	13	Marble bed	Limestone scrubbing	15.4	17	23	15	45	40
Will County 1	3.5	15	Venturi	Limestone scrubbing	17.5[b]	50	15	20	15	35
Stock Island	2.0	0.04	Mechanical collector	Limestone scrubbing	2.4	20	5	74	1[c]	50
La Cygne	5.3	22	Venturi	Limestone scrubbing	12.5	40	15	30	15	35
Cholla	0.5	10	Flooded disc scrubber	Limestone scrubbing	3.1	15	20	0	65	50
Paddy's Run 6	3.7	14	Electrostatic precipitator	Lime scrubbing	5.3	94	2	0	4	40
Mohave 2	0.4	10	Electrostatic precipitator	Lime scrubbing	1.5[b]	2	95	0	3	65

[a] Ref. 16

[b] Prior to stabilization

[c] Mainly unburned carbon

usage other than gypsum production, fly ash will have to be added to provide the pozzolanic properties necessary for structural qualities.

2.3 Potential Product Applications

Technical developments for the potential usage of the sludge have been made for the most part by: the Coal Research Bureau at the University of West Virginia under the sponsorship of the EPA; the G&WH Corson Company (now IUCS) near Philadelphia, Pennsylvania; and Combustion Engineering, Windsor, Connecticut. Uses being studied or considered include those for which fly ash is being used or could be used, plus new developments. The following lists provide a summary of those considerations, and include uses that may be possible regardless of how slight their potential is. The first category presents applications in which fly ash has been used:

1. Concrete admixture (structure and products).
2. Manufacture of Portland cement.
3. Fired brick.
4. Filler in bituminous concrete.
5. Road base course, parking lots, etc.
6. Structural fill.
7. Soil amendment.

8. Mine void fill.

9. Neutralization of acid mine drainage.

The second category includes potential new uses for sludge:

1. Autoclaved products - gas concrete, bricks, mineral aggregate.

2. Hot press sintering - pipes, metal coatings.

3. Gypsum products - wallboard, plaster.

4. Mineral recovery.

5. Sulfur or sulfuric acid production.

6. Artificial aggregate.

2.4 Use-Inhibitions

The difficulty associated with the small usage of fly ash in the United States and the weak projections for the potential use of sludge products are best seen by examining the inhibitions to the use of fly ash and the comparison of fly ash properties with those of the sludge. It has been determined that the major inhibitions to the use of fly ash, which generally apply to the inhibitions to the use of sludges, are:

1. Highly variable chemical and physical properties.

2. Lack of control or availability of usable supply when needed.

3. Necessity for appreciable capital expenditures to classify, handle, store, or process materials.

4. High transportation costs.

5. Inability to economically compete with other materials.

Although it has been shown that there are many uses for the fly ash, considering already developed technologies, and that these potential products are in many ways equal or superior to existing materials (Ref. 3), its actual utilization has been limited. The situation is not improved for FGD sludge, as described in the following discussion.

Relating the potential technical uses of the sludge to the basic properties and qualities previously mentioned in Subsections 2.2 and 2.3, various factors are applicable regarding the potential utilization of large tonnages of sludge on a national basis. These factors identify reasons wherein the sludge product is expected to be technically or economically inferior to a fly ash product (which is already in a weak marketing position as shown in Table II-1), where its production or use may create a pollution problem, or where it may be technically sound but not economically competitive on a wide scale. These factors are:

1. The sludge is produced in a wet state and will have to be dewatered or dried for many uses to prevent

agglomeration due to the interaction of the pozzolan with self-contained lime in the presence of water. Agglomeration can require a grinding operation depending on fineness required for structured concrete qualities.

2. Its pozzolanic properties for concrete product applications are reduced because the fly ash content and consequently the glassy phase is reduced.

3. Sludge properties can be highly variable; therefore, blending may be required for many applications.

4. The use of sludge in the manufacture of sintered products has three distinct disadvantages:

    a. Sulfur is released and would have to be collected.

    b. Decomposition of sulfates (or sulfites) takes place at temperatures below sintering and results in the physical destruction of the "green formed" product.

    c. The fusion temperature is such that a short range exists between sintering and melting, thereby requiring a sophisticated temperature control system for the sintering process.

5. The soluble salt content of the sludge presents a potential problem of leaching heavy metals to groundwaters for certain applications such as soil amendment and acid mine drainage neutralization.

6. The technology for mineral recovery to obtain aluminum (Ref. 1), iron, titanium, silicon, and lime is undeveloped or very costly.

7. Severe competition exists from a saturated current market for products such as gypsum,* mineral wool (Ref. 3), sulfur, and sulfuric acid (Refs. 3, 8).

8. High capital investments are necessary to produce autoclave products.

In consideration of the factors noted, it should be recognized that of all the potential large scale uses for sludge, the most promising are: (1) road base materials (Refs. 5, 6, 10, 12) and artificial aggregate (Ref. 9), and (2) landfill or land reclamation when appropriately conditioned to prevent leaching (Refs. 8, 9, 11, 13). The former are considered commercial utilizations of the sludge while the latter is generally considered a disposal process. As a road building material, sludge has a potential for large tonnage utilization; however, it must compete with existing materials such as crushed rock and bituminous concrete (Ref. 3). Although the sludge-produced road base materials are believed crack resistant when compared to competing products, crushed rock in particular is acceptable by most specifications and agencies and is less expensive. Only in local areas where rock is not available or allowed would sludge materials have a ready market. Artificial aggregate could also consume large masses of the sludge, but its demand is only local where natural aggregate is not available. In the near term, this is not expected to be a widespread condition.

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*The only sludge product sold overseas is gypsum which is marketed in Japan where the material is competitive (Refs. 4, 17). It is projected that in Japan in the mid-1970's, the sludge-gypsum supply will exceed demand (Ref. 4).

In summary, because scrubber sludge is not expected to find large scale commercial outlets in the near term, it is concluded that the major consideration must be disposal. Although utilization is desirable in the long run, near term treatment/disposal solutions must occupy a higher priority.

B. PRESENT AND PLANNED UTILITY INDUSTRY DISPOSAL PROGRAMS

Sludge disposal is a problem to a portion of the utility industry regardless of whether or not it presents a pollution problem because of quantities of materials that must be handled and disposed of. Utilities currently operating or planning installation of a lime/limestone scrubbing system must consider many factors such as:

Nonuniform environmental standards invoked by local regulatory agencies.

Variations in sludge chemical and physical properties resulting from varying properties of process ingredients (coal, sorbent, water); variations in types of ash collection and scrubbing processes.

Disposal site location and ownership; sites not owned by the utility company generally require more stringent treatment.

Disposal site geotechnical and meteorological factors; proximity to ground and surface waters, topography, soil permeability, and rainfall/evaporation.

These factors (not necessarily a complete list), which affect the technique and cost of sludge disposal, indicate that no single solution may be applicable to all sludge disposal situations. As a result, utility companies have taken different approaches toward solution of their site-specific disposal problem.

Table II-3 summarizes the dewatering and final mode of sludge disposal that utilities have selected for specific lime/limestone installations. As can be noted, ponding techniques outnumber landfill disposal approaches by about a 3:2 ratio. Brief notes on selected installations representing specific disposal approaches follow:

Table II-3. SLUDGE TREATMENT/DISPOSAL TECHNIQUES FOR SELECTED UTILITY LIME/LIMESTONE FGD SYSTEMS

(C = Current; P = Possible Additions)

Facility (Availability Status)	Sorbent	Fuel	Scale	Dewatering Technique					Final Disposition	
				Clarifier	Filter	Centrifuge	Dryer	Pond	Ponding	Landfill
TVA-Shawnee (Current)	Limestone & lime	Eastern coal	Prototype	C	C	C			C (Unlined)	
City of Key West-Stock Island (Current)	Limestone (coral marl)	Residual oil	Full					C		C (Unfixed)
Commonwealth Edison Co.-Will County (Current)	Limestone	Eastern coal	Full	C	P		P	C (Clay lined, well points)		C (Fixed)
Southern California Edison-Mohave Lime: Current Limestone: Oct 1977	Limestone & lime	Western coal	Full	C	C				C (Fixed)	
Kansas City Power & Light-Hawthorn (Current)	Boiler injected limestone	Coal (possible E&W blend)	Full	C				C (Well points)	C (Unlined)	
Kansas Power & Light - Lawrence (Current)	Boiler injected limestone	Eastern coal	Full					C	C (Unlined)	
Louisville Gas & Electric Paddy's Run (Current)	Carbide sludge ($Ca(OH)_2$)	Eastern coal	Full	C	C					C

Table II-3 (Continued). SLUDGE TREATMENT/DISPOSAL TECHNIQUES FOR SELECTED UTILITY LIME/LIMESTONE FGD SYSTEMS

(C= Current; P = Possible Additions)

Facility (Availability Status)	Sorbent	Fuel	Scale	Dewatering Technique					Final Disposition	
				Clarifier	Filter	Centrifuge	Dryer	Pond	Ponding	Landfill
Northern States Power - Black Dog (Current)	Limestone	Western coal	Pilot	C					C (Unlined)	
Kansas City Power & Light - LaCygne (Current)	Limestone	Eastern coal	Full						C (Unlined)	
Arizona Public Service - Cholla (Current)	Limestone	Western coal	Full						C (Unlined) (Solar evap)	
Duquesne Light - Phillips (Current)	Lime	Eastern coal	Full	C				C (Curing) (Unlined)		C (Fixed)
Detroit Edison - St. Clair (Jan. 1975)	Limestone	Eastern coal	Full					C		C (Unfixed)
TVA - Widows Creek (1976)	Limestone	Eastern coal	Full					C	C (Unlined)	
Ohio Edison - Bruce Mansfield (1975/1976)	Lime	Eastern coal	Full	C						C (Fixed)
Northern States Power - Sherburne (1976/1977)	Limestone fly ash	Western coal	Full	C					C (Clay lined)	

Commonwealth Edison (Will County)

Commonwealth Edison has the most industrial experience with disposal of stabilized sulfur oxide sludges. The full-scale limestone scrubber is installed on Will County's Unit 1 boiler (163 Mw). The disposal problem at this station is compounded by the unavailability of sufficient acreage to contain the sludge, the immediate proximity to the Illinois River, and a high water table. Commonwealth Edison has decided that the sludge must be conditioned so that it will not leach to the groundwater and that it must serve adequately as a landfill material because the final disposal is planned on land which is not owned by the power company.

Commonwealth Edison has consulted with several commercial sludge processors but, because of the economics involved, they are attempting to develop their own fixation process with the aid of the Chicago Fly Ash Company, under contract to carry out the stabilization and disposal operations (Ref. 18). Chicago Fly Ash has employed the Civil Engineering Department of the University of Illinois for assistance. During periods of scrubber operation, clarifier overflow is recycled to the scrubber system via an interim pond and underflow sludge is pumped directly into a ready-mix truck to which the fixation ingredients are added, and mixed enroute to one of two cure ponds where the materials are unloaded. The present additives are reported to be approximately 10 percent lime and 20 percent fly ash on a dry basis. The cure ponds are clay basins approximately 3 meters deep (10 feet) and total about 28,000 m^2 (7 acres). An arbitrary lining thickness of about 0.3 m (1 foot) was chosen. The clay has a permeability coefficient of about 10^{-6} cm/sec, whereas the cured material is expected to have a coefficient in the range of 10^{-7}-10^{-9} cm/sec. The material cures for approximately 1 month and is inspected by local authorities to obtain permission for off-site disposal. Criteria for permission is unknown at this time. After permission, material will be dredged from the basin and hauled to a nearby landfill area while the other basin is being filled.

When the scrubber is not in operation, the disposal process continues, dredging up old sludge accumulated during early periods of scrubber operation in the 7 acre pond adjacent to the clarifier. The ponded sludge, settled to 50 percent solids, is dredged up with a front end loader and taken to an open hopper equipped with a drag chain feeder. From the hopper the material is conveyed to a point directly above a ready-mix truck which receives the sludge and the dry additives before proceeding to the on-site disposal basin.

It is not yet known whether the sludge may pose an environmental hazard. Liquors are saturated in sulfate, and chloride content is about 800 ppm. Corrosion assisted erosion was experienced at this concentration but use of rubber-lined piping and pumps in the recirculation system is reported to have eliminated the problem. Tests are being conducted to improve the final product by the elimination of cracks during curing and to verify impermeability in the field. It has not yet been determined whether the leachate contains trace heavy metals. It has been reported that with enough lime, a concrete-like product with 3000 psi strength can be obtained. For landfill disposal purposes, a product with a strength far less than this is desired because of the subsequent need to dredge it from the cure pond. Data are not currently available.

The cost of the current operation has varied between approximately \$5.25 and \$10 00 per ton of wet sludge (50 percent solids). At the recent EPA enforcement hearings on power plant pollution control, a utility spokesman cited an average cost of

$17.10/dry ton, equivalent to about $8.55/wet ton (50 percent solids). The higher end of the range probably reflects specific case operations which include machinery breakdown and repair. These costs are only operating and maintenance costs and do not include pond costs and capitalization. It appears that the present philosophy is conservative in order to avoid possible problems due to variability in sludge chemistry. The utility hopes to optimize for steady-state operation taking into account scrubber down-time. A development program is planned with the aim of reducing costs by increasing fly ash and reducing lime contents. Additionally, a pug mill will be used to intermix additive ingredients with the sludge and the ready-mix truck will be replaced by a dump truck. It is believed that a vacuum filter must be installed between the clarifier and pug mill to reduce the water content of the sludge. Unofficial estimates for disposal, including all costs, after optimization and achievement of steady-state operation, are about $6.00-6.50/wet ton. Adequate determination of the technical quality of the fixed materials and attendant costs are not expected for at least a year.

Duquesne Light (Phillips)

Sludge samples from a small pilot lime scrubber system at Duquesne Light's Phillips Station have been tested and characterized by the Dravo Corporation. For the full scale SO_x scrubbing system, which started up in the spring of 1974, the sludge disposal method entails a stabilized (fixed) landfill operation in conjunction with clarification and curing ponds as dewatering methods. Sludge is removed as underflow from the clarifier at 35-40 percent solids, treated with Calcilox (a Dravo additive) and allowed to set for about 30 days in one of three clay-lined curing basins. A disposal development program is being conducted at Phillips to evaluate the planned landfill approach. The cured sludge is dredged from the curing basin and hauled to the test site in an inactive ash disposal area approximately 1 mile away. The site includes two ponds lined with Hypalon. Each pond has underdrainage and overdrainage piping to collect liquor for testing.

At a recent symposium it was reported that the interim ponds fill up more rapidly than anticipated, and as a result a greater proportion of additive and fly ash is needed to give a shorter curing time. This resulted in a 10-14 day period for curing instead of the planned 28-30 day period. The consolidated sludge is trucked to the test site and deposited in one of the lined ponds. However, 6 additional weeks of curing was found to be necessary before the sludge could be leveled because of the thixotropic nature of the material, thus slowing down the disposal process considerably. Consequently, not all sludge can be put into the sludge ponds; some is mixed and compacted with dry fly ash on the normal ash disposal area. Leachate monitoring results will be presented in Section 2.0 (Ref. 19).

Although not definitive, sludge disposal costs have been estimated at approximately $3.00 per ton of coal burned; the basis for this estimate is not known. Utility spokesmen recently reported that disposal costs actually incurred ranged from $15 to $20 per ton on a dry basis, or $7 to $10 per ton of wet sludge (Ref. 19). Estimates are believed to include capital costs, common landfill site for fly ash and sludge, compaction, covering with top soil, and seeding. Recently, at the EPA enforcement hearings on power plant pollution control, a Duquesne spokesman cited $14-15/dry ton of sludge for disposal. At 30 percent solids loading this is equivalent to about $4-5/wet ton of sludge, or $7.25/wet ton at 50 percent solids.

Duquesne Light appears to have one of the more comprehensive research and development programs with respect to sludge disposal. However, specific physical and chemical analyses to be performed are not currently known and results are not expected to be available for at least a year (Ref. 20).

Kansas City Power and Light (Hawthorn)

The full-scale boiler-injection limestone scrubbers on Units 4 and 5 at Kansas City Power and Light's Hawthorn Station operate under closed-loop. Ponding is used both as a dewatering technique and as final disposal. An experimental sludge pond has been constructed; 14 well points have been placed outside the perimeter (Ref. 8). A monitoring study is being carried out in conjunction with Combustion Engineering to determine possible adverse effects on the groundwater. Samples of groundwater were to be taken weekly for 2 months prior to introduction of sludge to the pond, and to continue for 1 year thereafter. Preliminary data are not available but it is believed that results to date are inconclusive because the general area may be heavily contaminated by the absorption of leachates from fly ash ponds on the plant site.

Northern States Power (Sherburne County)

Northern States Power is currently employing ponding operations to dispose of the sludge and ash from the pilot-scale limestone scrubber at Black Dog Station (Ref. 21). Clarification is used for primary sludge dewatering. The pilot operation is a research effort primarily to determine scrubber parameters for the Sherburne County Station. Sludge treatment and disposal considerations are not known.

At the Sherburne County Station, sludge generated by two limestone scrubbers of the 1360 Mw total capacity, planned for start-up in 1976 and 1977, will also be disposed of by ponding. At this site clarifier underflow sludge will be sluiced to clay-lined basins and excess water will be recycled to the scrubber system (Ref. 22, 23). The scrubbing system will use two stages--a variable throat venturi estimated to remove 55 percent of the SO_2 and 90 percent of the particulates, and a marble bed scrubber estimated to remove an additional 15 percent of the SO_2 and remaining fly ash. Because the coal ash contains about 17 percent CaO, fly ash removal and SO_2 control will be done simultaneously at a low limestone stoichiometry (about 20 percent). The use of fly ash as a sorbent predicated the collection of particulates in the scrubbing unit. However, it is believed that newer plants would use precipitators for fly ash removal for increased operating flexibility, reduced erosion, potential sales of dry ash, and allowance for single stage scrubbing.

An initial 10-year pond will be approximately 263,000 m^2 (65 acres) with 12 meter (40 foot) high dikes. A second pond will be added in the future, bringing the total capacity to about 468,000 m^2 (165 acres) for an expected 35-40 year plant life. Nearby clay will be used to line both ponds with an approximate 46 cm (18 inch) thickness. The disposal site is located on bluffs above the Mississippi River at an elevation of 294 meters (965 feet). Normal river elevation is 280 meters (920 feet). Definitive disposal costs are not available. However pond costs (including clay) are believed to be in excess of $30,000 per acre. Although the utility's plans are not clear, the possibility exists that the Sherburne County Station disposal method will undergo environmental monitoring by the analysis of leachate from wells placed around the pond.

Louisville Gas and Electric (Paddy's Run)

The current and future sludge disposal practices for the Paddy's Run Station of Louisville Gas and Electric involve landfill operations. The full scale scrubber, utilizing carbide sludge [$Ca(OH)_2$], is operated closed-loop and is installed on a 70 Mw unit fired with a 3.5-4 percent sulfur, 15 percent ash Kentucky coal. All sludge is being collected independently of fly ash. Precipitators exist on all stacks and are planned for future plants. The sludge disposal process includes extracting underflow from the clarifier at ~25 percent solids, vacuum filtration to 40-55 percent solids, and trucking in company-owned 12 ton dump trucks about 1 mile to an off-site disposal area (borrow pit) excavated by the Kentucky Highway Department. Fly ash is sometimes mixed in with the sludge by bulldozer at the disposal site. The sludge is about 95 percent calcium sulfite and oxidation of the liquor is retarded such that the sulfate in the liquor is about 400 ppm. Because of the poor settling characteristics of the sulfite, flocculent is added to the clarifier and has reportedly been used successfully. The sludge receives no stabilization treatment or other environmental control. There are no apparent plans for monitoring this disposal approach. Costing for this disposal is not well defined; however, it is believed that the hauling cost is approximately $0.50/wet ton at this particular site.

Future plans may include stabilization; the utility is looking at processes commercially offered by Dravo and IUCS. Research in the area may be underway by the University of Kentucky and the state highway department (Ref. 24). The use of fixed wastes in land salvage of strip-mined areas or as a support material for recovery of the 30-60 percent of the coal remaining in deep mines is being considered by the utility. Alternative disposal schemes being considered include collection of clarifier underflow at 20-30 percent solids and addition of dry-collected fly ash to increase solids content to 50-60 percent; filtration to about 50 percent and possibly subsequent addition of fly ash; and piping the solid waste slurry to the final disposal site (Ref. 24).

Southern California Edison (Mohave)

At Southern California Edison's Mohave Plant, two small pilot systems have been operated to evaluate both lime and limestone scrubbing. Both Dravo and IUCS have been involved in treatment/disposal of lime and limestone sludges from these pilot units, respectively. When the full scale units are operating, current plans are for each vendor to treat and dispose of the sludge from a scrubber module (about 160 Mw equivalent). Dravo will fix lime sludge and dispose of it by on-site landfill estimated to have about 1 year storage capacity. Liquor will be recycled to the scrubber. IU Conversion Systems (IUCS) will stabilize limestone sludge, convert it into aggregate and haul it away. In addition, dewatering techniques including centrifugation and vacuum filtration will be tested. Cost data is unavailable. Monitoring plans are not known.

Ohio Edison (Bruce Mansfield)

At Ohio Edison's Bruce Mansfield Plant, lime scrubbing will control the SO_2 from two 880 Mw units of generating capacity. The utility has contracted with the Dravo Corporation for property purchase, site preparation, and detailed design of the sludge disposal process. Current plans are to remove clarifier bottoms sludge at about 30 percent solids and add boiler collected fly ash, lime grits from the pulverizer and slaker, and Calcilox additive to bring the total solids content to about 32 percent. The composite slurry will then be pumped about

10 km (6.5 miles) to a large landfill site behind a 400 foot high embankment. Supernatant liquor will be recycled to the scrubber system. The disposal site is estimated to have a 30 year life. Definitive disposal costs are not available although Dravo estimates \$2-4/ton of coal burned for a generalized cost estimate, which includes capital investment ranging from \$30 to 60 million. It is not known whether the utility plans to evaluate the environmental adequacy of their disposal approach.

TVA (Widows Creek)

At TVA's 550 Mw Widows Creek limestone scrubbing facility (to be started up in 1976) a new pond is under construction which will have an initial 7-year capacity of 3.4 million m^3 (120 million ft^3). This can be increased by 1.0 million m^3 (35.3 million ft^3) by raising the dikes. An estimated additional 2.7 million m^3 (95 million ft^3) of capacity, for which no provision has yet been made, may be needed before 1995. A total of 0.93 km^2 (230 acres) of land is taken up by the new pond which is sectioned for separate disposal of ash and sludge. The pond is unlined, and the perimeter and divider dikes are 9.1 meters (10 yards) tall with 1.2 meters (3.9 feet) of freeboard and are constructed of compacted earth. Under closed-loop operation, the scrubber wastes will be pumped to the sludge disposal section of the pond as a 15-16 percent solids slurry. The ash pond effluent will be released to the Guntersville Reservoir. A thickener will not be employed. A final settled density of 40 percent solids is expected, based on pilot plant data showing 57-66 percent water content after 240 days of settling. The overall disposal rate is calculated to be 115 m^3/hour (4050 ft^3/hr) at full load. Monitoring plans are unknown.

City of Key West (Stock Island)

Experience in untreated sludge disposal has been obtained at the City of Key West's Stock Island facility where a limestone scrubbing process has been installed on the 37 Mw unit. Residual oil is burned, thus resulting in a solid waste of low ash content. The scrubber solids are placed in one of two settling ponds where drying takes place (Ref. 25). Plans are that while one pond is being filled, the other is emptied. The filling time for each pond is 21 days. Originally the dredged, semidried sludge was to be dumped in an adjacent 81,000 m^2 (20 acre) city-owned bay-bottom site of approximately 81,000 m^2 (20 acres). To date, neither pond has been dredged, but the material will have to be disposed of in compliance with a Florida state law which prohibits filling of submerged land productive to marine life. No firm decision has been made regarding a long-term approach for sludge disposal.

Arizona Public Service (Cholla)

Because of the climatic conditions at Arizona Public Service's Cholla facility, a solar evaporation pond is being used as a sludge disposal technique. The 115 Mw limestone scrubber system generates sludge at the rate of 3.1 metric tons per hour on a dry basis. The system is operated closed-loop relative to the sludge recirculation tank but open-loop with respect to the pond. A bleed stream from the scrubber recirculation tanks is sent to two sludge storage tanks which are emptied about once per shift to the existing ash pond where solar evaporation and settling are responsible for dewatering (Ref. 16).

Mitsui Aluminum Company

For purposes of comparison, the Mitsui Aluminum Company's installation is discussed here. Two dual-stage venturi scrubbing systems utilizing carbide sludge as an absorbent have been retrofitted to the 156 Mw power plant. Closed-loop, continuous operation has been demonstrated since March 1972, with no scaling or plugging problems. A bleed stream from the system containing mostly calcium sulfite (80 percent) and calcium sulfate is disposed of in a preexisting 90,000 m^2 (22 acre) ash pond (Ref. 26). This pond was constructed by excavating a filled area next to the sea, forming a dike 16 feet high. Since the outer wall of this dike is ~50 feet from the sea, the inner wall was lined with a vinyl film to prevent leaching through the wall (Ref. 27). The water table (sea level) is anywhere from 1 to 23 feet below the pond bottom depending on the tide. Pond liquor which is saturated with respect to calcium sulfate is recycled via rubber-lined piping to the scrubber for reuse. The ponded sludge, which in some cases will support the weight of a man, remains a very thixotropic material about 6 inches below the surface. Now that successful performance of the SO_2 control system has been achieved, production of high quality gypsum by incorporating a proprietary oxidizer is being considered. There is currently a definite market for by-product gypsum in Japan.

In summary, it appears that firm decisions for the total disposal problem have not been made by some utilities. Those that have selected an approach either will not commit sludge to the disposal site for a period of time during which changes can be made, if necessary, or are uncertain of the approach they have chosen. Neither the utilities nor the sludge conditioning processors are expected to readily identify all environmental problems, solutions, or economics associated with sludge disposal. In all likelihood, detailed information will be especially difficult to obtain from those utilities with a sludge disposal problem, because of concern for regulatory pressures. An EPA program for testing and evaluation of sludge treatment/disposal techniques is necessary to upgrade the environmental effectiveness and cost-effectiveness of these techniques and to correlate information with that obtained from utilities or sludge conditioning processors.

C. DISPOSAL BY PONDING

Disposal of wastes by ponding has historically been a favored technique in a number of industries; e.g., gypsum sludge from fertilizer plants, phosphate slime from phosphate mining, and fly ash from coal burning facilities. The mechanics of pond construction and pond operation are well known. However, many current pond operating techniques were established with less regard for environmental effects than is now considered appropriate (although they are not representative of the best available control technology). There are two major environmental aspects associated with ponding of sulfur oxide sludges which require consideration: (1) the water pollution potential associated with soluble species in the sludge liquor and solid phases, and (2) the land deterioration associated with nonsettling sludges. In the past, there was often little attention paid to pond site selection or to pond lining. The general attitude seemed to be that fine particles from the pond liquor would eventually plug the soil and minimize percolation. However, careful study of pond sites is now required and, when there is a danger of groundwater pollution, suitable pond linings must be provided. Changes in regard to pond overflow may be especially significant. In the past, dilution by the receiving stream was considered to provide acceptable treatment. Regulations are moving toward a "no degradation" basis which means pond overflow must be eliminated in almost all cases. This will require total recycle of pond liquor.

One advantage of ponds is that the volume can be increased as needed by building up the sides of the pond. In some cases (e.g., gypsum sludges from the fertilizer industry) the pond walls can be built up using settled solids from within the pond. In the case of scrubber sludges this may require special treatment (stabilization by addition of chemicals which undergo pozzolanic reactions with the sludge). Ponded scrubber wastes are typically not stabilized; however, stabilization of that sludge used for building up the walls via certain commercial processes (discussed in Subsection II-D 1.2) might provide a suitable approach.

1.0 Survey of Technical Features of Ponding

In addition to consideration of factors such as geology, topography, and hydrology necessary for site selection, the basic technical features involved in the design and operation of all ponds include the following:

1. Sluicing of material to pond.

2. Settling.

3. Pond lining.

4. Pond management.

The general characteristics of each of these technical areas are described below with special emphasis placed on those aspects specifically dealing with scrubber sludge.

1.1 Sluicing Operations

Transport of waste scrubber sludge to the ponding site is carried out in most cases by sluicing operations; i.e., piping the slurried solids. Individual sludge properties such as viscosity, velocity, temperature, composition, particle size, and solids concentration affect the pumping characteristics of the material. Also of major concern is the distance to be covered. Special problems specifically related to sulfur oxide sludges such as corrosion or erosion potential also require investigation.

In general, the transport of solids in pipes depends on the use of a carrier fluid to transmit pressure from the pump or compressor to the solid being moved. The viscosity of the material greatly influences the transport characteristics, since it is a measure of a resistance to flow. The viscosity of a number of individual scrubber sludges has been determined; the data were presented in Section I-E of this report. Specific characteristics such as thixotropic or rheopectic behavior unique to some scrubber sludges are related to viscosity and, therefore, will influence sluicing operation parameters. For instance, sludges with high sulfite composition exhibit thixotropic behavior. This observed loss of viscosity with stirring would result in lower head loss at constant velocity of the fluid. A different sludge, however, has been shown to exhibit rheopectic behavior. This would tend to have an adverse effect on pumping operations.

In addition, the critical velocity for a particular sludge must be determined, since it is the flow velocity at which solids are most economically moved for a given pipe size. This velocity will occur somewhere in the turbulent flow region; i.e., the region in which particles may move in any direction with respect to each other.

Other technical aspects of pipelining of sludge requiring consideration prior to design of a system are materials of construction and possible use of pumping aids. In addition, transport can be accompanied by erosion problems due to the physical nature of the solids. In many installed lime/limestone systems, much of the piping, blades, and pumping equipment used to transport slurries are rubber-lined to protect against the abrasive properties of the slurry, especially in pipes carrying sludges of higher solids content.

The use of long distance piping systems is increasing rapidly since the demonstration of technical and economic feasibility. Table II-4 summarizes commercial applications which have been installed in recent years.

The economics of solids handling by sluicing or piping operations depends mainly on two factors: amount to be handled and distance to be covered. Thompson et al. reported total pipeline transport costs (including power, labor, supplies, and capital charges) to range from $1.76 per dry metric ton of sewage sludges (3.5 percent solids) for a 40 kilometer, 900 ton/day system to a maximum cost of $22 per dry metric ton for a 160 kilometer, 91 metric ton/day system (Ref. 28).

The results of a 1970 nationwide survey of 22 utilities show that it was costing $0.033 to $1.21 per metric ton (average of 25 plants, $0.50/metric ton) to sluice ash to the on-site disposal area (Ref. 8). Another survey in which off-site waste disposal costs were reported gave figures in the range of $0.01 to $0.10 per cubic meter per kilometer ($.05-0.50/1000 gal.-mile) for pipeline conveyance of brines and sludges (Ref. 29). These costs did not include fees charged by the receiving agency. The author of the report concluded that pipeline conveyance

Table II-4. SUMMARY OF COMMERCIAL SLURRY PIPELINES[a]

Pipeline	Location	Material	Length (miles)	Diameter (inches)	Throughput (million tons per year)	Solids (specific gravity)	Weight (percent solids)	Years in Operation or Status[b]
Consolidation Coal	Ohio	Coal	108	10	1.30	1.40	52	6[c]
American Gilsonite	Utah	Gilsonite	72	6	0.38	1.05	46	11
Rugby Cement	England	Limestone	57	10	0.70	2.70	61	5
Columbia Cement	Columbia	Limestone	9.2	5	0.35	2.70	55	25
South African Companies	South Africa	Gold tailings	21.5	6 & 9	1.05	2.70	50	14
Savage River Mines	Tasmania	Iron concentrate	54	9	2.25	4.90	60	2
Black Mesa Pipeline, Inc.	Arizona	Coal	273	18	5.70	1.40	50	In startup phase
Hyperion Wastewater Treatment Plant	Los Angeles	Digested sewage sludge & effluent	7.5	22	-	1.80	1.0	11
Mogden Wastewater Treatment Plant	England	Digested sewage sludge	7	12	-	1.80	4.0	33
Easterly Pollution Control Center	Cleveland, Ohio	Raw sludge	13	12	-	1.80	2.5	32

[a] Ref. 28.

[b] As of 1971.

[c] Commercial operation ceased in 1963 for non-technical reasons. Now maintained in standby condition.

is the most economical mode for quantities in excess of 100 cubic meters (26,000 gallons) per day irrespective of distance.

Lord of Dravo Corporation cited a cost for slurry pipeline transportation of SO_2 scrubber sludge, exclusive of capital investment costs of $0.02/ton mile of wet sludge handled (Ref. 30).

1.2 Settling

Physical properties and settling characteristics of scrubber sludges have been discussed in Section I-E.

1.3 Pond Lining

Pond linings have been finding greater favor in recent years. In some cases the intent has been to decrease pollution; in other cases the intent has been to avoid loss of water which could be recycled. In many areas, clay, concrete, wood, or metal has been used as a liner. Recently, synthetic linings are finding increasing usage. These include the following materials which are offered in different formulations (Ref. 31).

Polyvinyl Chloride

A rough, highly puncture-resistant material. It resists flame, many chemicals, oils, greases, ozone, solvents, abrasives and microbiological activity. It has good weatherability and high strength-to-weight ratio. However, exposure to heat causes various degrees of chemical degradation; it is susceptible to staining by sulfides; adhesion to metal or wood is poor; low temperature increases stiffness.

Natural Rubber

One of the oldest sheet-lining materials. It has high tensile strength and good chemical resistance but somewhat poor resistance to sunlight.

Synthetic Rubbers

Butyl and EPDM rubbers are highly impermeable to water, very flexible, and durable. They resist wear, tear, ozone, and aging and have a wide range of operating temperatures and excellent weatherability. They have low resistance to petroleum solvents and aromatic and halogenated solvents. These rubbers are denser than natural rubber and neoprene and are suitable for higher temperature conditions.

Hypalon rubber is a chlorosulfonated derivative of polyethylene and was developed to withstand the combined effects of weather, oil, and several chemicals. It resists puncturing, abrasion, tearing, ozone, aging (ultraviolet), and has very good weatherability. It has comparatively low tensile strength.

Neoprene rubber is quite similar to natural rubber but has better resistance to certain combinations of oils and acids.

Polyethylene

This plastic is tough, highly flexible, inert to solvents, and resistant to low temperatures. It has poor weatherability and puncture-resistance. It has high elongation but may become thin in localized areas under tensile stress. Polyethylene is available in three types--low, medium, and high density and as chlorinated polyethylene.

Polypropylene

This material offers a balance of properties rather than any one outstanding characteristic. It has good chemical and heat resistance, high tensile strength, high flexibility, and low permeability to water. It has poor weatherability and poor resistance to oxidizing solvents.

Nylon

Nylons have good heat resistance, a wide range of operating temperatures, low permeability to water, high tensile strength, and good flexibility. Their moisture absorption is high and weatherability poor. They resist most oils and chemicals except acids.

1.3.1 Lining Selection - In selecting a liner, many specific criteria must be designated, including the following (Ref. 31):

1. The liner should have high tensile strength and flexibility and should be able to elongate sufficiently without failure. It should resist abrasion, puncture, and the fluid to be stored, and should conform to other desired physical properties.

2. It should have good weatherability and a guaranteed long life.

3. It should be immune to bacterial and fungus attack.

4. It should be able to stand the desired temperature variations and other ambient conditions.

5. It should be capable of being repaired easily at any time during its life.

1.3.2 Leak Detection for Lined Pond - Sometimes a leak detection system must be built into the pond system, especially when toxic or polluting chemicals are to be stored. Two types of leak detection systems are (Ref. 31):

1. Underbed Drainage System. This consists of a network of gravel-packed drainage canals or perforated drainage pipes. All seepage is channeled to the outer perimeter of the pond and collected in

a sump outside the pond where inspections can be made. A variation is to monitor the fluid in standpipes (piezometers) placed within the pond. The tops of the pipes extend above surface level; the bottoms penetrate the liner into the underlying soil. Wells in the proximity of the ponds may also be utilized, although considerable leakage may have occurred before well water analysis indicates the problem.

2. Ground-Resistivity Measurement System. Several metallic pins may be buried beneath the pond. Using a resistivity meter, ground resistivity between these pins may be measured. A marked decrease in ground resistivity may indicate pond leakage.

1.3.3 Lining Costs - Some approximate cost figures have been estimated for lined ponds. Factors influencing the price include size and type of lining required. A 1974 cost estimate for a 46 cm (18 inch) thick clay liner installed in several large ponds in the Midwest was \$10.80/m^2 (\$9.00/yd^2). The clay was transported by truck about 48 km (30 miles) from the clay pits to the pond site. If suitable clay had been available on-site, the lining could have been constructed for \$1.80/m^2 (\$1.50/yd^2) (Ref. 32). The cost of clay lining for a 0.02 to 0.04 square kilometer pond (enough storage for about 10 Mw equivalent) would then amount to \$36,000 to \$72,000 utilizing clay on-site.

Other sources of installed liner costs provided the preliminary data presented in Tables II-5 and II-6. It should be noted that these cost data employed 1973 dollars and may not represent current costs; however, relative cost comparisons should be valid.

Figure II-1 presents typical lining cost data for installed liners at the field site. The wide range of costs for each type of lining results from varying labor costs, varying transportation costs, and price discounts for large purchases (Ref. 32).

Figure II-2 shows the 30 year average disposal cost as a function of the depth of raw sludge in the pond. Two liner materials were considered for comparison: 0.508 mm (20 mil) thick polyvinyl chloride (PVC) at an installed cost of \$2.33 per square yard including a soil cover of 15 cm (6 inches) and 0.762 mm (30 mil) thick Hypalon at a cost of \$3.85 per square yard installed. The pond configuration used had a 0.9 meter (3 foot) freeboard. It was assumed that the land need for 30 year disposal operations would be purchased initially, but the ponds would be constructed each 10 years as the previous one became full. The land costs used were \$404 and \$2020 per hectare (\$1000 and \$5000 per acre). Figure II-2 illustrates the effect of land cost on ponding costs and also indicates that there is an optimum sludge depth which would result in a minimum disposal cost.

Very recent data (January 1975) indicate an installed cost for 30 mil unsupported Hypalon in a 1-10 acre pond of \$6.00 to 7.20/m^2 (\$5.00 to 6.00/yd). The cost savings realization for a larger pond is indicated by the fact that the same lining for a 100 acre pond would cost about \$4.80/m^2 (\$4.00/yd^2). The

Table II-5. PRELIMINARY ESTIMATE OF COSTS OF POTENTIAL LINERS FOR SANITARY LANDFILLS

POLYMERIC MEMBRANES - PLASTICS AND RUBBERS[a,b]

Type	Cost, $ per square yard				
	Thickness, mils (in.)	Price of Roll Goods	Fabrication Costs[c]	Field Installation Cost	Installed Cost[d]
Butyl rubber, unreinforced	31.3 (1/32)	$2.25		$1.08- 1.71	$3.33- 5.04
	46.9 (3/64)	2.70			
	62.5 (1/16)	3.33			
Chlorinated polyethylene (CPE), unreinforced	20	1.58		0.99- 1.26	2.57- 3.51
	30	2.25			
Chlorosulfonated polyethylene (Hypalon) w/nylon scrim	20	1.39		0.72- 1.08	2.56- 4.41
	30	1.66			
	45	2.61	0.45		
		2.88			
Ethylene propylene rubber (EPDM), unreinforced	31.3 (1/32)	2.00		1.17- 1.71	3.17- 4.91
	46.9 (3/64)	2.42			
	62.5 (1/16)	3.20			
Neoprene, unreinforced	31.3 (1/32)	2.07		2.24- 2.43	4.31- 5.40
	46.9 (3/64)	-			
	62.5 (1/16)	2.97			
Polyethylene film	10	0.36		0.63	0.99- 1.35
	20	0.72			
Polyvinyl chloride, unreinforced	10	0.52		0.54- 0.99	1.06 2.32
	20	0.90			
	30	1.33			

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[a] Ref. 33

[b] Represent 1973 dollars

[c] Cost of fabricating rolled sheeting into panels.

[d] Soil cover not included; all of these polymeric membranes require some soil cover, cost of which can range from $0.10 to 0.50 per square yard per foot of depth.

Table II-6. PRELIMINARY ESTIMATE OF COSTS OF POTENTIAL LINERS FOR SANITARY LANDFILL SOILS, ADMIXTURE MATERIALS, AND ASPHALT MEMBRANES[a]

Type of Liner	Cost, $ Per Square Yard		
	Materials	Installation	Installed[b]
Soil + Bentonite (Volclay)[c]			
9 lbs/sq yd (1 psf)	0.06	0.66	0.72
18 lbs/sq yd (2 psf)	0.12	1.05	1.17
Soil Cement			
6 in. thick + sealer (2 coats, each 0.25 gal./sq yd)			1.25
Soil Asphalt			
6 in. thick + sealer (2 coats, each 0.25 gal./sq yd)			1.25
Asphalt Concrete - Dense-graded paving with sealer coat			
Hot mix - 2 in. thick			1.20 - 1.70
Hot mix - 4 in. thick			2.35 - 3.25
Asphalt Concrete - Hydraulic			
Hot mix - 2 in. thick			1.50 - 2.15
Hot mix - 4 in. thick			3.00 - 4.20
Bituminous Seal (catalytically blown asphalt)			
1 gal./sq yd	0.27		1.50 - 2.00 (with earth cover)
Fabric sealed with asphalt emulsion[d] (Polypropylene mat sprayed with asphalt emulsion)	0.70-0.77	0.56 - 1.10	1.26 - 1.87

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[a] Ref. 34

[b] Without earth cover, except as noted. Costs can range from $0.10 to 0.50/yd^2 per foot of depth.

[c] Amount needed depends on type of soil available at or near the landfill site.

[d] Depends on size of job.

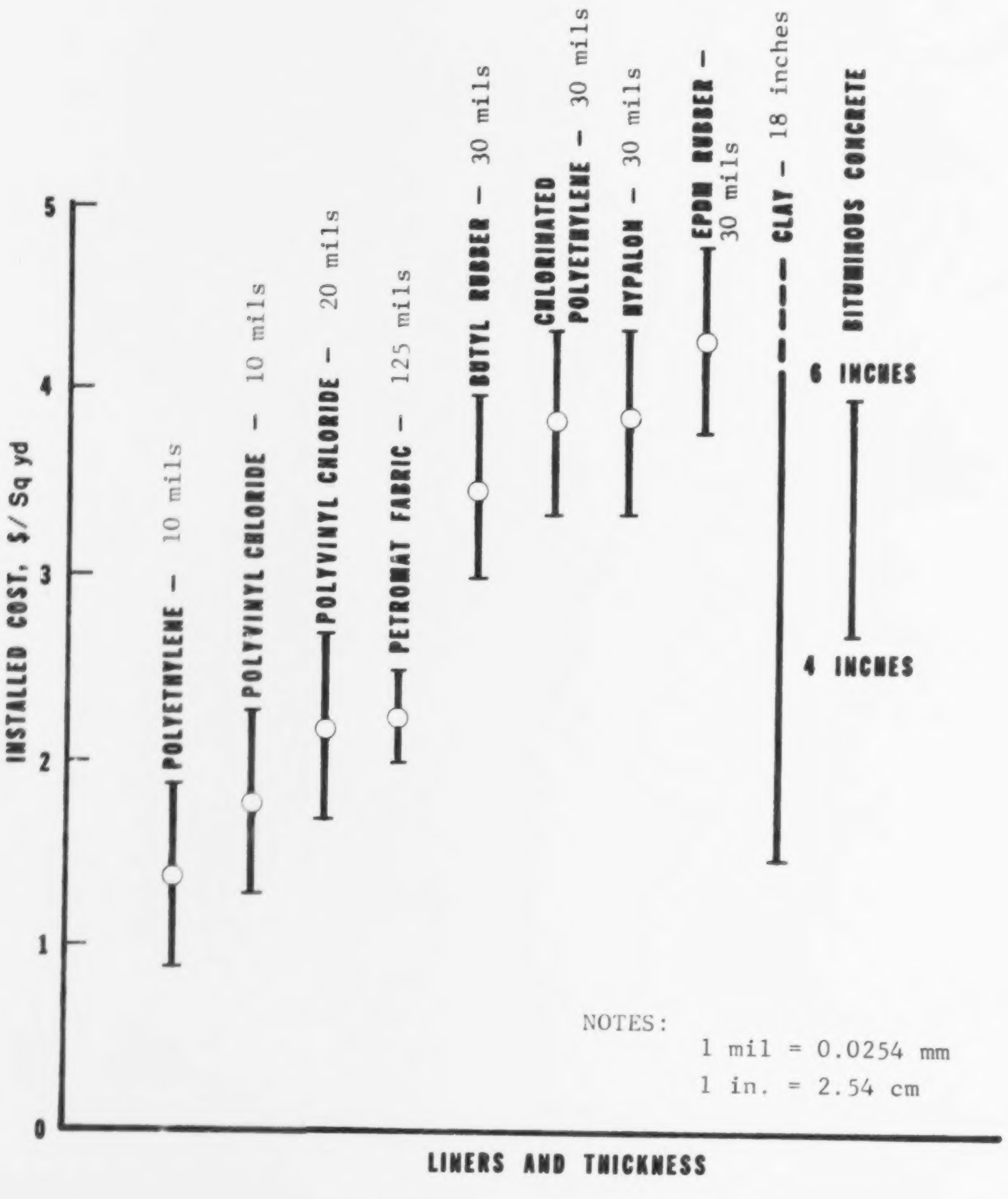

Figure II-1. Installed Liner Costs (Ref. 32).

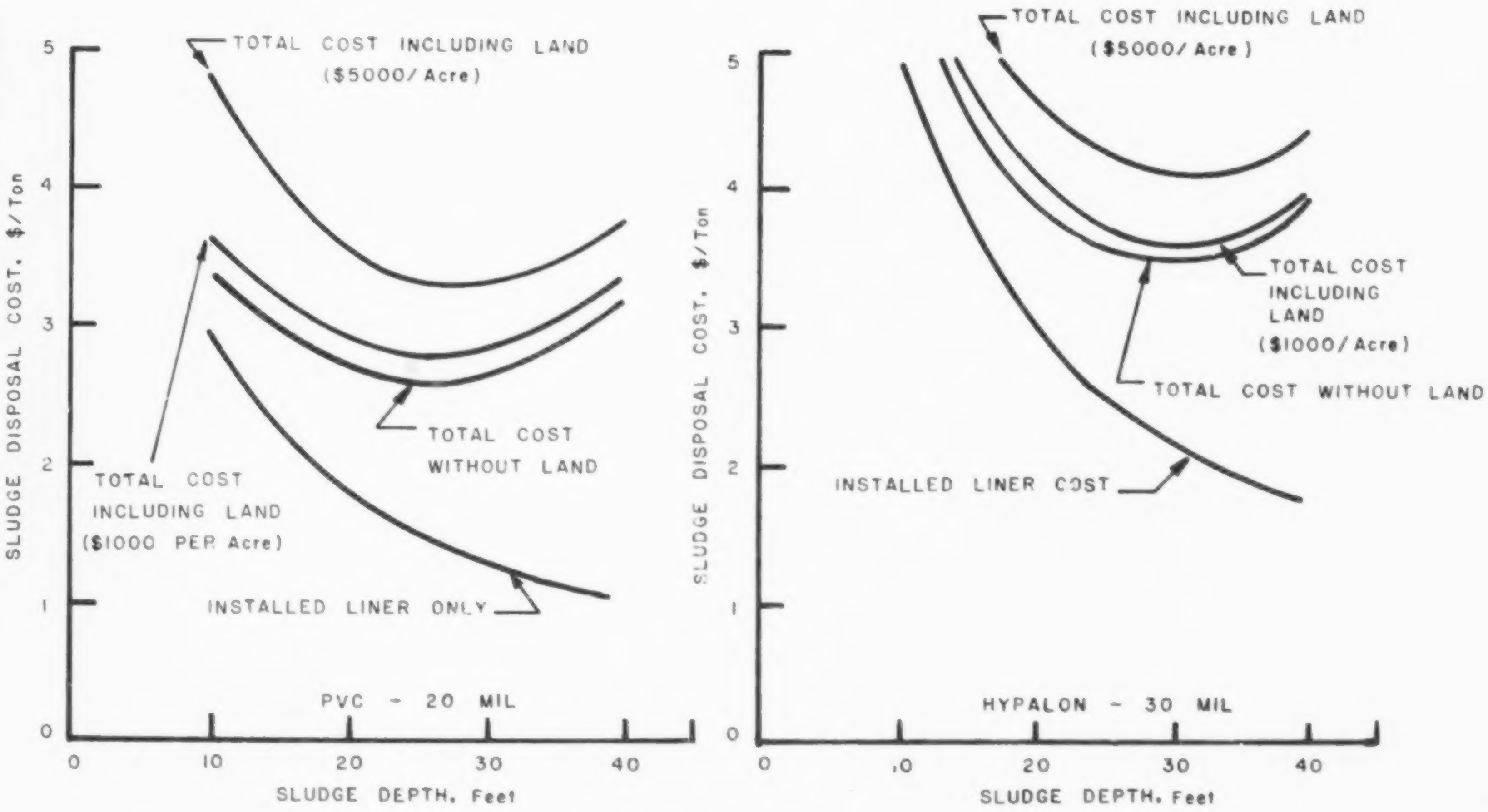

Figure II-2. Disposal Costs - Ponding Sludge, 50 Percent Solids (30 year average) (Ref. 32).

cost for 30 mil fabric-reinforced Hypalon for the smaller pond of 0.40 to 4.0 hectares (1-10 acres) would be \$6.80 to 7.90/m^2 (\$5.70 to 6.60/yd^2); for a 40 hectare (100 acre) pond the cost would be about \$5.74/m^2 (\$4.80/yd^2) (Ref. 35).

These cost figures when compared to those in Figure II-1 indicate the recent cost escalation of materials, emphasizing the fact that the data are useful for relative comparisons, but may not be valid for design purposes.

Generally, the costs presented to not include the costs for site and surface preparation nor the cost of ground cover, which would be required in almost all cases. The surfaces on which the liners are to be placed must be graded and smoothed for drainage and compacted to prevent settling of the ground below the liner materials: i.e., soil asphalt, soil concrete, and the asphalt concretes. The cost of site preparation is essentially the same for all the liner systems, though it is possible that some of the liner systems may not require as much effort in surface preparation as others. An earth cover, preferably one which is somewhat porous, would appear to be needed as a part of the liner system. Such soil covers will thus allow the large landfill equipment (e.g., caterpillar tractors and compactors) to operate on the liners.

With the exception of liner applications noted in Section II-B, there are no known applications of liners for ash or sludge disposal. Consequently, performance data on liner materials for sludge disposal applications is not available. However, Voyer and Cluff (Ref. 36) noted that the seepage rate of Wyoming Bentonite clay exposed to high concentrations of calcium and magnesium salts increased to 0.1 to 0.4 inches/day after the first year and to 5.5 to 9.0 inches/day after 4 years.

More data is required, but this 25- to 50-fold increase suggests that permeability of clay may increase significantly with time.

Additionally, the environmental requirements of liner materials and consequently their cost-effectiveness is not well defined. As a point of reference, $\$1.0/yd^2$ is equivalent to about \$5/Kw capital cost and 0.15 mills/Kwh annual cost for a ponded sludge (with ash) from a 1000 Mw coal-fired unit (Table I-8, Column 5) based on 15 years storage life, 10 feet deep.

1.4 Pond Management

The start-up and day-to-day operation of a disposal pond involves answers to the following questions pointed out by Slack and Potts (Ref. 7).

1. Will the pond be operated as a single unit or divided into sections?
2. Will the original depth be the limit or can walls be built up using the settled material?
3. Will the pond be partially filled with water before operation begins?
4. Can the pond be filled to the top of the dike or must some freeboard be allowed?

The first question is related to the settling characteristics of the material as previously discussed (Section I-E). Ash ponds are typically operated such that the slurry enters one end of the single pond. As it flows to the opposite side, the well-settling ash drops out and a pool of supernatant forms at the far end. The effluent is removed via weirs or standpipes, thus allowing continuous operation of the pond until full. In contrast, waste gypsum from phosphoric acid manufacture is usually ponded in several units. Since the settling characteristics of the waste are poor, one pond is allowed to dry and be emptied while another pond is being filled. This may also be necessary in ponding of sulfur sludge.

The second question deals with the dimensional stability of the settled material. In ash pond management, the settled ash is seldom used to extend the height of the walls because its spherical form results in a low angle of repose. Waste gypsum, on the other hand, lends itself readily to this application. Excavating equipment is employed to pile up the dried material as high as 30 meters. Preliminary data for untreated scrubber sludges presented in Section I-E are not yet sufficient to predict whether this type of operation could be successfully applied.

If the scrubber is operated in a closed-loop mode, smooth start-up may necessitate partial filling of the disposal pond beforehand This would provide a source of recycle water at the onset of operation and eliminate the need for additional start-up pumping arrangements. This would produce overall increasing concentrations with respect to composition of liquor associated with solids until steady-state is achieved.

The amount of freeboard required for any particular pond is chiefly a function of climate. If the area receives large amounts of precipitation during periods when evaporation rate is low, then more freeboard would be necessary than for ponding operations in hot dry climates. Ponds which lack drainage provisions would also tend to require greater freeboard.

2.0 Potential Water Pollution Aspects of Ponding

Potential problems associated with contamination of surface and/or groundwaters by untreated sulfur oxide sludges exist in the following areas:

1. Soluble trace elements.
2. Chemical oxygen demand due to sulfite oxidation to sulfate.
3. Excessive total dissolved solids.
4. Excessive levels of specific species; e.g., sulfate, chloride, carbonate, calcium, and magnesium.
5. Excessive suspended solids.

These could present problems via leachate and/or run-off routes.

The composition of the leachate formed is a function of several factors including composition of coal, limestone, and make-up water; chemical composition of the sludge solid phase; pH; and solubility of the individual species present. The nature of the leachate from untreated sludge can be judged by examination of liquors associated with scrubber samples, especially clarifier supernatant or scrubber recycle liquor in closed-loop operation. Data indicate that many of the potentially leachable elements originate with the coal. For this reason, examination of liquors associated with ash ponds also provides some insight into potential leachate compositions. Available chemical analyses for untreated sludges and ash have been presented earlier in Section I-E of this report. The potential problems associated with a ponding operation are discussed below. Although leachate and run-off are similar in nature, they are considered separately in this report.

2.1 Leachate From Sludge Disposal Ponds

An unlined disposal pond provides a potential for contamination of groundwater. Unlike a landfill, the sludge is always saturated with water, and the "head" of liquor in the pond assures a continuous driving force for percolation. Underlying strata may also become saturated; and if an unconfined aquifer exists beneath the pond, the pond site may act as a "recharge" zone for that aquifer. If no unconfined aquifer exists, the pond liquor may continue to seep into the existing strata beneath the pond. It is not clear whether this would be construed as a detrimental environmental impact.

Given that an aquifer does exist, the important factors are the rate at which pond liquor permeates into the groundwater and the chemical composition of that liquor as it enters the aquifer (any suspended material will probably be filtered out by the soil).

It should be noted that movement of groundwater can be very slow; e.g., about 1 meter per year laterally. It also is important to note that groundwater movement may occur in a "plug flow" fashion. Given that a pollution source exists above an aquifer, under some circumstances vertical flow of polluted water into the aquifer may be greater than the natural lateral movement of the groundwater. This, plus the "plug flow" nature of groundwater, means that there may be little opportunity for dilution of the polluted water even over a period of years. This situation is very different from the case of allowing pond overflow to enter a stream, where even high pond liquor concentrations may be diluted in a matter of minutes.

With regard to groundwater contamination by constituents of pond liquor, there are some possible mechanisms to reduce the impact of the pond liquor. These involve a group of reactions commonly referred to as "soil attenuation" mechanisms. Reactions between solution species and soil particles can occur via adsorption, ion exchange, or precipitation. Since ion exchange and precipitation are essentially displacement of one ion by another, only simple adsorption provides a true removal mechanism. For ion exchange and precipitation, it is to be hoped that a toxic species might be lost from solution and a less toxic species gained; however, there is no assurance of this. It is unlikely that a large change in total dissolved solids would occur via soil attenuation mechanisms. Some dissolved species such as heavy cations might, however, move through the soil slower than the liquid in which they entered. Other species, generally anions such as NO_3^-, PO_4^{-3} and especially Cl^-, which may not enter into adsorption or exchange reactions, would move through the soil faster than the liquid in which they entered. The law of electroneutrality requires that any leachate (ionic solution) must contain an equivalent quantity of cations and anions. Unfortunately, no data are yet available on this important topic for scrubber sludge liquors although the soil type is clearly important. STEAG, a government organization in Germany, has instrumented a disposal pond for lime scrubber sludge to determine effects on groundwater. This group has been visited and a description of their system is presented in Reference 37. So far their monitoring system has not detected any contamination of the aquifer which is located only about a meter below their unlined pond. However, their observation wells are far enough away from the pond that sufficient time probably has not elapsed for any contamination to reach the wells.

Combustion Engineering and Kansas City Power and Light are also doing a study of this type, but no results have been released. A large study of soil attenuation mechanisms is being done for municipal wastes under the sponsorship of EPA's Solid and Hazardous Waste Research Laboratory (SHWRL). Their experimental program is just getting underway, however, and no results are yet available. There is one piece of information which, although not well documented, seems to be of significance in regard to pollution of groundwater by leachate. That is that no pollution problems have been documented due to ash pond leachate, even though ash ponds without liners have been widely used in all types of soils for decades. Even though no problems have been attributed to ash ponds, the information on the chemical properties of sludge indicates a need for proper site selection and possibly lining of ponds. In some situations a continuing monitoring program may be necessary; for example, when a disposal pond is to be located over an unconfined aquifer.

2.2 Overflow of Pond Liquor

Disposal ponds have typically been operated with less than total recycle of pond liquor. The excess liquid has often been permitted to flow into receiving streams with little treatment beyond neutralization, settling, or skimming. In addition, spills have occurred frequently.

Newer and more stringent regulations on waste water disposal will likely reduce the practice of overflowing excess liquor into lakes and streams. This will necessitate the use of closed-loop (total recycle) operation for scrubber sludge disposal by ponding, with treatment of any blowdown (purge) streams. Alternatively, blowdown streams might be disposed of via evaporation, deep well injection, or disposal in the ocean. This sort of operation, combined with proper site selection, design, and lining of ponds, should eliminate contamination of surface or groundwater by ponded scrubber sludge, thus minimizing any water pollution problems associated with sludge ponding. A potential problem would be the eventual land reclamation of the pond site due to the resistance to dewatering exhibited by many unstabilized sludges. This problem might be particularly troublesome in those areas with high annual rainfall and low annual evaporation; this is discussed further in Section II-D. Sludge dewatering techniques are currently under investigation in an effort to make sludge a suitable disposal materials.

D. DISPOSAL BY LANDFILL

A second approach to the problem of disposal of waste solids generated by lime or limestone scrubbing systems is landfill. Currently less than 40 percent of existing or planned installations have adopted this alternative, while approximately 60 percent have included ponding facilities.

Characterization of lime/limestone scrubber sludge thus far has revealed a nature not readily suitable to untreated landfill disposal. The sludge does not settle or dewater readily, and the preliminary results of one experiment have indicated that once dried, the untreated material will reabsorb moisture to its original water content (see Section I-E). A second aspect of untreated sludge is its leachate characteristics, also discussed in Section I-E. For these reasons, chemical and physical stabilization processes are being marketed and are now being demonstrated. The marketing agents for these fixation techniques claim that conversion to a physically and chemically stable landfill material is possible. In some cases, a salable by-product is reportedly made.

In the following discussion, the term landfill will mean the disposal of a scrubber sludge treated via dewatering and/or stabilization techniques.

1.0 Survey of Technical Features of Landfill Disposal

The technology associated with disposal of waste scrubber sludges by landfill operations is currently in the development stage. There are three basic features requiring discussion to accurately describe the current state of technology regarding this disposal method: dewatering, stabilization, and handling of sludge.

1.1 Dewatering Techniques

The object of any sludge dewatering process is to recover the solid content of the sludge in a concentrated form suitable for disposal or further processing. The liquid content is recovered from suspended solids for recirculation within the process or for safe discharge as a processed effluent. Presented in this section of the report is a discussion of methods available for dewatering of air pollution control system sludges. Many of these techniques have been experimentally and industrially applied to sludges generated by lime or limestone wet scrubbing systems. Table II-7 is a summary of the results of some of these recent studies.

Table II-7. SUMMARY OF SLUDGE DEWATERING TECHNIQUES

Method	Application	Sludge	Results	Comments	Reference
Clarification	Currently used as primary dewatering device on full-scale systems	Various lime and limestone scrubbing system sludges	Limestone sludges thicken "better" than lime because of coarse unreacted additive present		Ref. 14
	Bench-scale	Shawnee limestone system sludge	20% solids achieved		Ref. 38
Bed Drying	Bench-scale column	Limestone system sludge	Steady state drainage rate was 0.046 cm^3/min. Sludge with "relatively" high sulfate content settled to 67% solids with or without underdrainage. High sulfite sludges settled only to 52% solids with underdrainage	Air-dried sludge exposed to water regained original moisture (51.7%)	Ref. 38
Centrifugation	Bench-scale tests	Various lime-scrubbing system sludges	47-57% finals solids content (original: 19-44%)	Fly ash was present in the samples	Ref. 14
	Bench-scale tests (short-term)	Limestone scrubbing system sludge	53-64% solids achieved (feed was 10-29% solids)		Ref. 7 Ref. 39
	Full-scale	Chiyoda process sludge (high sulfate/sulfite ratio)	85-90% solids achieved		Ref. 7
	Comparative laboratory - scale	Various limestone system sludges	Shawnee sludge: solids content increased from 20 to 65%. Western plant's sludge: > 65% solids achieved	Although original water contents of sludges were similar, better results obtained with Western plant sludge were believed to be due to its lower water content at maximum density	Ref. 38

TABLE II-7 (Continued). SUMMARY OF SLUDGE DEWATERING TECHNIQUES

Method	Application	Sludge	Results	Comments	Reference
Vacuum Filtration	Bench-scale	Limestone scrubbing	65-75% solids achieved		Ref. 38
	Bench-scale	AMD neutralization sludge	Solids content increased from 0.6 to 23%	Problems with cake blocking filter were experienced	Ref. 40
	Bench-scale	Pilot plant limestone scrubbing system samples	55-60% solids content was achieved	Compare to 38% solids with settling alone. Thixotropic nature of sludge caused filter cake to rewater upon release. Cake cracking in early stages prohibited further dewatering. Removal of cake from filter was difficult	Ref. 7 Ref. 40
	Pilot-scale; in conjunction with clarification	Double-alkali system (General Motors)	53% solids average		Ref. 41
	Full-scale; in conjunction with clarification	Carbide sludge system (Louisville Gas and Electric)	35-45% solids		Ref. 42
Thermal Drying	Commercial	SO_2 fly ash removal process	90-95% of original water content (70%) removed; i.e., achievement of 90-95% solids is claimed		Ref. 43

Interim Ponding

An interim pond has three purposes. It is a clarification basin, a sludge dewatering area, and a sludge storage area. A single pond cannot perform all of these functions effectively. The effectiveness of ponding as a dewatering technique is a function of the settling characteristics of the sludge. This aspect has been dealt with in Section I-E.

Clarification (Thickeners)

Thickeners are currently employed in most sulfur oxide removal systems as a primary dewatering device in cases where the solids content is low. Thickeners are sized in terms of the surface area per rate of throughput; e.g., if a particular slurry settles slowly, a longer time and consequently a greater surface area is required to effectively provide separation of solids and liquor. The thickener surface area can vary from 1.0 to 10 m^2/metric ton/day (Ref. 14) depending on the settling characteristics of the sludge. Limestone scrubber sludges are reported to thicken well compared to lime sludges because of the coarse limestone present, but are associated with a turbid supernatant. Therefore, the design should be based on clarification considerations. On the other hand, zone settling rates should be the basis for design of thickeners for sludges consisting of more uniformly fine particles.

Thickener underflows for various types of sludges vary in weight percent solids and bulk density. Results have been reported for a number of FGD system sludges following 1 day's settling, and are reproduced below (Ref. 14). One fly ash sample is included for comparison.

Sludge Source	Wt % Solids
Eastern Coal (with ash)	<30-45
Western Coal (no ash)	21.5
Dry Injected with Wet Scrubbing (with ash)	24
Limestone Scrubbing (no ash)	39
Smelter Gas	37-40
Fly Ash	64

Centrifugation

Centrifuges are well-suited for the separation of waste solids from a liquid suspension. This technique produces well concentrated cakes and offers a high degree of effluent clarification. Space requirements for equipment are minimal. However, they have the disadvantage of significant power consumption, and are mechanically complex.

A conveyor centrifuge can handle large quantities of solids, but at flow rates no higher than 757 liter/min (200 gal./min). The feed should be comminuted or macerated. The filter cake is removed by an internal conveyor. Therefore, the solids must pack well. Polymer coagulants must be added to soft packing solids.

A two-stage centrifuging process is advantageous when there are two types of solids present. It also provides flexibility against changes in solids quality.

Centrifugation has been investigated by Dravo, TVA, and EPA as a possible dewatering method for sulfur oxide sludges. A 75 percent solids content was achieved for various pilot plant samples employing a centrifugal force of 1000 X gravity (Ref. 7).

Short-term centrifuge tests conducted at EPA's test facility at Shawnee produced promising results. Limestone scrubber sludges from the clarifier bottoms were used. The results are shown in Table II-8 (Ref. 39). Long-term tests are planned.

Dravo Corporation conducted a series of tests on lime scrubbing sludges from Duquesne Light Company's Phillips Station using a Bird 6-inch continuous centrifuge. These results are given in Table II-9 (Ref. 14).

Because of the blocky physical nature of sulfate crystals as opposed to sulfite, dewatering is improved by a higher sulfate/sulfite ratio. Thus, good results (85-90 percent solids) have been reported for a sample obtained from the Chiyoda process, which results in a sludge with an extremely high sulfate/sulfite ratio. This process is based on aqueous scrubbing of SO_2 to produce sulfurous acid followed by oxidation to sulfuric acid. Reaction with limestone at this stage produces calcium sulfate; thus the sludge contains only negligible amounts of sulfite.

Aerospace Corporation has reported the results of a comparative study of dewatering techniques utilizing clarifier samples from Shawnee's limestone scrubber. The water content of the original sample was ~85 percent; centrifugation reduced the water content to 44 percent. Associated bulk densities were also determined, and the results are presented in Table II-10. A similar study was conducted with clarifier samples from a Western power plant's limestone scrubber; these results are also included in Table II-10. Although both clarifier samples contained approximately equal amounts of water, centrifugation resulted in greater reduction in water content with the Western plant sample. The reason suggested for this was the physical nature of the sludge. As a result, maximum

Table II-8. SUMMARY OF SHORT-TERM CENTRIFUGE TESTS AT EPA LIMESTONE TEST FACILITY AT SHAWNEE[a]

Test Series	Machine Speed, rpm	Centrifuge Feed Source	Feed Rates gpm[b]	Wt % Solids in Feed	Wt % Solids in Cake	Wt % Solids in Centrate
I	2000	HF clarifier bottoms	11-22	15-22[c]	53-57	0.2-0.6
II[d]	2000	HF clarifier bottoms	10-22	16-24[c]	54-56	0.3-0.5
III	2000	HF clarifier bottoms	10-22	19-29[c]	58-61	0.1-0.5
IV	2500	HF clarifier bottoms	9-33	19-27[c]	60-63	0.1-1.1
V	2500	Scrubber bleed (clarifier bypassed)	11-35	10-14	59-63	0.1-0.6

[a] Ref. 39

[b] One gallon is equivalent to 3.785 liters.

[c] Increase the values by about 3 for pump seal water correction.

[d] Test Series II was a replicate of Test Series I.

Table II-9. CENTRIFUGE TESTS - PILOT PLANT SLUDGE[a]

Bird 6 in. Continuous Centrifuge

4130 RPM - 1400 G Force

Run No.	Feed Material[b,c,d]	Feed % Solids	Depth Pool	Feed Rate gpm[b]	% Solids	Effluent Solids %
1	Drum 8	33.6	Intermediate	3.4	47.8	4.6
2	Drum 8	33.6	Minimum	3.4	48.1	0.9
3	Drum 8	33.8	Maximum	3.4	47.3	3.4
4	Drum 8 (Diluted)	29.8	Maximum	3.3	50.1	0.8
5	Drum 8 (Diluted)	20.0	Maximum	1.1	50.2	0.2
6	Drum 8 (Diluted)	19.5	Minimum	3.3	50.2	0.6
7	Drum 13	44.3	Minimum	3.3	58.8	9.3
8A	Drum 13/14 (50% each)	42.3	Minimum	3.3	55.0	13.2
8B	8A Discharge	57.4	Minimum	-	59.5	9.2

[a] Ref. 14

[b] Drum 8: SiO_2 4%, CaO 43%, S 19.9%, SO_2 26%, SO_3 17.2%, CO_2 5.8%

[c] Drum 13: SiO_2 31.8%, CaO 18.2%, total S 7.5%, SO_2 8.8%, SO_3 8.0%, CO_2 2.8%

[d] Drum 14: Not Identified

Table II-10. COMPARISON OF DEWATERING TECHNIQUES FOR LIMESTONE SCRUBBER SLUDGES[a]

Technique	Shawnee Samples		Western Power Plant Samples
	Bulk Density (g/cm^3)[b]	% Solids	% Solids
Clarification	1.14 ± 0.02	20 ± 0.5	~20
Settling	1.3 ± 0.04	40 ± 0.5	(Freely Drained)
Centrifugation	1.4 ± 0.04	56 ± 0.5	>65
Vacuum Filtration	1.6 ± 0.05	64 ± 0.5	>65

[a] Ref. 38

[b] The true density of Shawnee solids is reported to be 2.48 g/cm^3.

density of Western sludge (1.87 g/cm^3) is achieved at a slightly lower water content (22 percent H_2O) than for the Shawnee sludge (1.7 g/cm^3 at 30 percent H_2O).

Vacuum Filtration

The most commonly used type of vacuum filter is the revolving drum. Some of the variables affecting the ability to dewater a sludge are:

Sludge Variables	Operating Variables
Concentration of Solids	Vacuum
Age	Amount of Drum Submergence
Temperature	Drum Speed
Viscosity	Degree of Agitation
Compressibility	Filter Media
Chemical Composition	Prior Conditioning of Sludge
Nature of Solids	

When vacuum filtration was applied to various pilot plant limestone sludge samples in TVA labotatories, 55-70 percent solids contents were achieved. Original solids content and sulfate/sulfite ratio were not reported. Typical filtration rates employed were 2000-2200 liters/hr/m^2 (Ref. 7). These results compared favorably with 38 percent solids obtained by settling alone. Considerable problems were encountered, however, because of the thixotropic nature of the sludge (Ref. 39). When the vacuum was released, the filter cake rewatered. Also, cracks formed in the filter cake in early stages of filtration which prohibited further dewatering. A third problem of difficult removal of the cake from the filter cloth may possibly be eliminated by air blast discharge.

Dravo Corporation (Ref. 14) employed a drum-type vacuum filter with a vacuum maintained at 50.8 cm Hg. They encountered problems with cracking of the filter cake and consequent disruption of filtration efficiency; this same problem was observed by TVA. Cracking tendency varied with the filter cake thickness; e.g., a lime scrubbing sludge sample cracked when 0.95 cm thick. Another problem observed was the thixotropic nature of the filter cake. Typical solids content of the cake was 45-55 percent, but could be increased to 60 percent with manipulation. The thixotropic nature was still retained, however, since sulfite crystals were present.

The belt filter is an improved version of the rotary drum filter in which the filter medium is removed from the drum after the dewatering portion of the cycle is completed and passed over a small roller to effect cake removal. The filter medium has a longer life and is constantly clean for filtration (Ref. 44).

Pressure Filtration

After piloting several processes for dewatering secondary digested sludge, the City of Cedar Rapids, Iowa, selected a pressure filter system for its new full scale water pollution control plant. Design capacity is about 18 tons/hr of 48 percent solids from a 5.5 percent solids sludge. Nine months' performance data with both utility fly ash and incinerator sewage sludge ash, with and without chemicals, indicated that pressure filtration of waste water sludges is an effective and economical process. However, the state of knowledge for this technology is still very limited and applicability to scrubber sludge or other materials is unknown (Ref. 45).

Thermal Drying

Thermal drying of sludges is accomplished by the introduction of hot gases to remove the moisture from the solid. The four types of dryers used are fly ash, multiple hearth, rotary drums, and atomizing spray dryers. All of these units are capable of drying waste water sludges to less than 10 percent moisture. However, due to the high fuel requirement, thermal drying is economically unattractive compared to other methods. A range quoted for the capital and operating costs for a heat drying sewage sludge treatment is \$28-44 dry metric ton (Ref. 40).

Koch Engineering Company currently markets an SO_2/fly ash control process involving a unique sludge dehydration operation (Ref. 43) in conjunction with a wet limestone or other alkali scrubbing system. The clarifier underflow having a typical solids concentration of 30 percent is pumped to the dehydrator where atomization occurs via a unique apparatus. The atomized slurry passes downward concurrently with the hot flue gases ($\sim 149^{\circ}C$) through the unit. The water content of the waste is reduced by 90-95 percent. The dry powdered solids are removed from the bottom. Fly ash is also removed along with the scrubber solids in this process.

1.2 Sludge Fixation

Chemical fixation of scrubber sludge and related materials is currently being marketed by several commercial groups including Dravo Corporation, IU Conversion Systems (IUCS), Inc., Chemfix Corporation, and Factory Mutual Research Corporation. Information available regarding the chemical and physical nature of lime/limestone scrubber sludge indicates a need to investigate such stabilization techniques. Quantitative data describing various properties of untreated scrubber wastes are presented in other sections of this report. Basically, these data seem to indicate a tendency for untreated, dewatered sludge to rewater upon contact with an aqueous environment. In addition, leaching and permeability features of dried sludges pose potential environmental hazards. The ability of proposed fixation techniques to prevent rewatering and leaching from treated sludges is under investigation. The current status of the fixation techniques now being marketed is described here.

IUCS offers several fixation processes based on the pozzolanic reaction between fly ash and lime (Ref. 9). Poz-O-Pac®, the original process on which sulfur oxide sludge fixation technology was based has been industrially applied to the stabilization of fly ash for production of structural materials. Three basic chemical reactions are involved: (1) the reaction between the fly ash silica and hydrated lime to form cementitious hydrated calcium silicates, tobermorite; (2) the reactions between soluble salts present in fly ash with lime and the alumina content of fly ash glass; and (3) aggregate addition resulting in mechanical support.

Poz-O-Tec* is an IUCS commercial process for the stabilization of fly ash using sulfur oxide sludges in addition to lime; the end product is called Sulf-O-Poz®. The chemistry is reportedly comparable to that describing Portland cement technology. Calcium sulfate reacts preferentially with calcium aluminates or calcium ferrites resulting in hydrated calcium sulfoaluminates (ettringite) or sulfoferrites, respectively. The cementitious reactions which take place in the Poz-O-Pac® process also are an important feature of the Poz-O-Tec* process. Sulfite ion, introduced in large quantities as magnesium sulfite or calcium sulfite in the sludge, acts as a catalyst in the cementitious reactions. Addition of aggregate may or may not be required, depending on the characteristics of the starting materials and the desired strength of the Sulf-O-Poz® product. This product is primarily a disposal material, but in some instances might be used as a structural material in land reclamation projects, structural embankments, etc. after a couple of weeks of curing (Ref. 45). Further processing of Sulf-O-Poz® is another alternative; utilization of the treated sludge as synthetic aggregate or road base material is then possible.

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*A service mark owned by IU Conversion Systems, Inc.

The Poz-O-Tec process can be retrofitted to existing power plant scrubber facilities. Application to most oil-fired systems is not feasible, however, since availability of fly ash is essential to the process. Conditions of relatively higher pH, as in lime systems compared to limestone, favor the reactions, although both types of scrubber sludges can be treated by the IUCS process (Ref. 38). The presence of soluble magnesium compounds introduced as dolomitic limestones is claimed to result in faster, stronger reactions because of the higher sulfate solubilities.

The initial step in the Poz-O-Tec process involves dewatering of the sludge by one or more of the techniques discussed in the preceding section. If fly ash is collected dry, addition to the sludge at this stage aids in the dewatering. If collection is by a wet method, the fly ash slurry may be introduced into the primary sludge dewatering device. The sludge/fly ash mixture is then conditioned with make-up additives which may include additional lime, limestone, fly ash, bottom ash, other sulfur oxide salts, and optional aggregate or other waste products. The output from the mixing and conditioning device is reportedly suitable for utilization as a stabilized fill material. The flow diagram for this process is shown in Figure II-3. This process is currently being demonstrated at Southern California Edison's Mohave Station where a full-scale limestone system is installed. More information may be found in Section II-B. Tests at other sites are being considered.

The economics of the fixation process offered by IU Conversion Systems have been presented by company officials (Ref. 9). Because of the many factors influencing the actual costs that would be incurred by a power plant utilizing this system, the estimated cost cannot be considered typical. Actual cost figures for full-scale disposal are not available.

Those factors affecting the cost of this or any other fixation process are given below:

1. Annual tonnages to be handled by the conversion process.
2. New boiler installation versus existing facilities.
3. The type of equipment selected for fly ash removal--for example, electrostatic precipitators versus wet scrubbers.
4. The chemical analysis of coal--sulfur, CaO, and ash contents.
5. Location of plant--on-site versus off-site.
6. Transportation costs--to and from conversion plant.

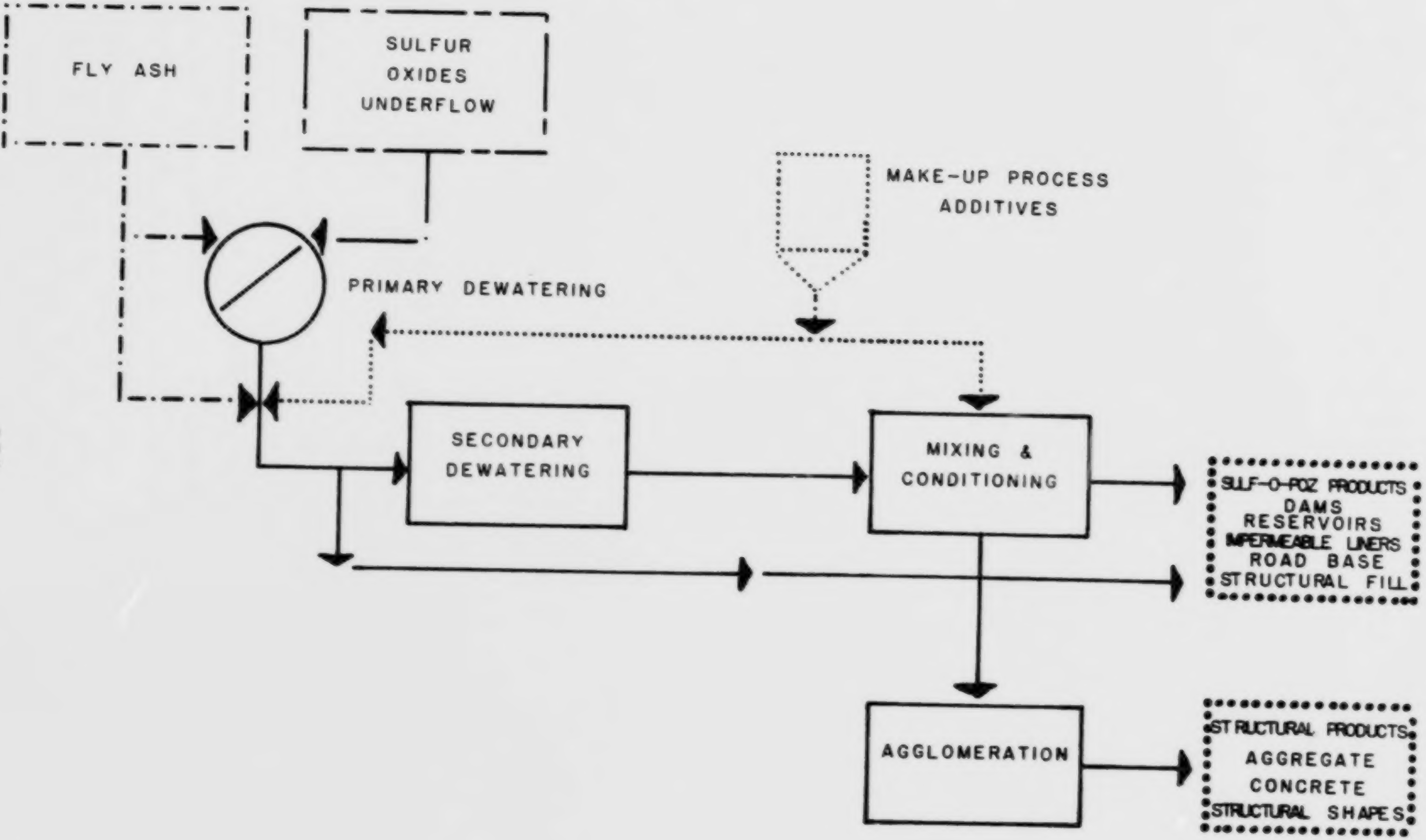
FLY ASH
SULFUR OXIDES UNDERFLOW
MAKE-UP PROCESS ADDITIVES
PRIMARY DEWATERING
SECONDARY DEWATERING
MIXING & CONDITIONING
SULF-O-POZ PRODUCTS
DAMS
RESERVOIRS
IMPERMEABLE LINERS
ROAD BASE
STRUCTURAL FILL
AGGLOMERATION
STRUCTURAL PRODUCTS
AGGREGATE
CONCRETE
STRUCTURAL SHAPES

Figure II-3. Schematic Diagram of Poz-O-Tec Process (Ref. 10).

7. Redundancy factor--duplication of equipment versus emergency holding basins, etc.

8. Type of scrubber--limestone versus lime.

9. Acquisition and cost of land.

10. Type of end product selected.

Based on estimates for newly installed plants in the range 1000-2000 Mw, burning coal with 3-4 percent sulfur and 10-15 percent ash content, and incorporating a lime or limestone scrubbing system, the cost estimated by the vendor to convert the sludge to a disposable Sulf-O-Poz® material is $4.00-5.00/wet ton (50 percent solids). This cost estimate includes capital investment and local transport charges (Ref. 32).

The sludge generated by the limestone wet scrubbing system installed on a 163 Mw unit at Will County Station is being disposed of by fixation and landfilling (Refs. 21, 40, 46). The treatment is based on addition of quicklime and fly ash. The spent scrubber slurry presently receives only primary dewatering treatment by clarification, although possible secondary treatment (such as vacuum filtration or thermal disc drying) is being considered to reduce the volume of sludge requiring fixation. Supernatant is returned to the system via an interim pond, while the clarifier underflow is pumped directly into a ready-mix truck in which lime and fly ash are blended with the sludge to produce a stable landfill material. This is transported by the truck to an on-site sealed basin. After curing for approximately 1 month, the material is inspected by authorities for permission for off-site disposal. Additional information concerning the Will County disposal operation may be found in Section II-B.

A recent cost estimate made by Commonwealth Edison for their Will County Station disposal operation was \$8.00-9.00/wet ton (50 percent solids) exclusive of capital costs. The utility also reported a worst operating cost of \$10/wet ton (50 percent solids) and a best operating cost of \$5.25/wet ton (50 percent solids). A target cost of \$6.00 to \$6.50/wet ton (50 percent solids) was projected (Ref. 32). The \$8.00-9.00/wet ton disposal cost is equivalent to \$3.92/ton of coal, 20.1¢ per 10^6 Btu, or 2.13 mills/Kwh (Ref. 18).

Dravo Corporation also offers a chemical fixation process for lime/limestone scrubbing waste products (Ref. 14). The product is a clay-like substance convenient for disposal. Much of their technology has been developed using sludge samples obtained at a pilot-scale lime scrubber operating at Duquesne Light Company's Phillips Station. However, sludges from additional sources have also been examined. The testing of their process has involved basic chemical and engineering evaluations for the sludge and treated product on a bench-scale level; industrial level testing is being conducted, but results are not yet available. The chemistry of the process has not been revealed because of current patent applications on the additive, Calcilox. The amount of lime-based additive required, however, is approximately 3-10 percent by weight of the dry sludge solids.

A Dravo spokesman estimated a typical cost to the customer for a pumping operation of <\$5.70/wet ton (50 percent solids). This cost includes land acquisition and capital costs, but it excludes land reclamation costs (Ref. 32). The capital costs involved are estimated at $30-60 million, and the total cost of disposal of ash and sludge is estimated to be equivalent to $2-4/ton of coal (Ref. 47).

Dravo evaluated two approaches to sludge disposal at Duquesne Light Company's Phillips Station. The first was for total disposal and consisted of taking clarifier bottoms, barging about 60 miles, reslurrying, treatment, and disposal at a Dravo-owned site. This approach was estimated to cost about $3.8-5.0 per metric ton of wet (30 percent solids) sludge including about 15 percent fly ash. The second approach was to design an on-site handling and treatment process for the utility's operation. Duquesne selected the latter approach and is purchasing the additive from Dravo which is acting in a consulting capacity. A Duquesne spokesman recently estimated the disposal cost for their trucking operation involving re-excavation from ponds at $7-10/wet ton (50 percent solids). Their capital cost was given as $124 per Kw (Ref. 19).

Ohio Edison has selected Dravo for disposal of the sludge generated at the Bruce Mansfield Plant estimated to be on line in 1975. A Dravo estimate for disposal costs at this facility was <$7.15/wet ton (50 percent solids). The estimate was based on considerable land acquisition and development and includes an 8 mile pumping operation (Ref. 32). Dravo is also involved in sludge disposal at Southern California Edison's Mohave Plant. More details on these applications may be found in Section II-B.

The Chemfix Division of Environmental Sciences, Inc. markets a proprietary fixation process for conversion of various industrial sludges to stable landfill with at least two inorganic chemicals, one liquid and one powder. The volume of additive needed is 10 percent or less of the volume of waste.

The system is based on the reactions between soluble silicates and silicate settling agents which react in a controlled manner to produce a solid matrix based on tetrahedrally coordinated silicon atoms alternating with oxygen atoms along the backbone of a linear chain (Ref. 48). Polyvalent metal ions react with Chemfix process chemicals resulting in a stable, conditioned sludge similar to those of Dravo and IUCS in that soluble constituents would be tied up and a material suitable for landfill is produced. Solidification into an inorganic compound is estimated to occur within 3 days although time can vary with the system being treated. The Chemfix process differs from that of IUCS and Dravo in that it produces a soil-like material that is permeable. Additionally, it can be landscaped in a manner similar to ordinary earth and can be seeded without requiring top soil. The other two processes require top soil for the final landscaping operation. The process, applied to nonscrubber sludges, has produced stable materials. Chemfix data indicate that the material produced does not leach chemical constituents by rainwater at concentrations that exceed the natural background levels in groundwaters (Ref. 32). Environmental Sciences acknowledges that chlorides and other highly soluble inorganic substances may present difficulties (Ref. 45). This aspect, however, will be discussed under Subsection II-D-2.0, Water Pollution Aspects of Landfill Disposal. The general experience of Chemfix indicates that solidified wastes when "cast" in place have fairly good load bearing capacities, but remolded wastes have poor characteristics. At present, Chemfix has not contracted with utilities for full-scale scrubber sludge disposal although their process is being tested on a smaller scale at EPA's test facility at Shawnee. The process has been industrially applied to metal finishing and electronics fabrication wastes and other types of nonutility industrial problems.

Typical costs for the Chemfix process have been quoted at $4-5/wet ton (50 percent solids). This includes all capital expenses and local transport costs (Ref. 32). A spokesman for Commonwealth Edison reported a Chemfix estimate of $5.90/wet ton (50 percent solids) for disposal of sludge at their Will County Station; this estimate was exclusive of local transport and landfill costs (Ref. 18).

Factory Mutual Research Corporation (FMRC) has a method of fixation of sludge employing the addition of a polymer structure to the sludge. No chemical reactions take place. The polymer essentially acts as a mechanical structure to thicken the sludge. The chemical reaction is begun when borax is added and causes a reaction within the polymer itself which filters out suspended particles as it shrinks. The rubbery material produced drains to about 50 percent solids and can be compressed to 75-80 percent solids. When added to water, the compressed material will fragment with time but will not reslurry (Ref. 49).

For each of the above processes, it is claimed that soluble components are immobilized in the treatment process. Specific data are reported by IU Conversion Systems and Chemfix and discussed in Subsection II-D-2.0. No leachate data from Dravo Corporation or FMRC are available at this time.

Comparative evaluations of several of these processes are currently being planned or carried out in the laboratories of Aerospace Corporation under contract to EPA (Contract No. 68-02-1010) and in an independent study by Combustion Engineering, Inc. Aerospace plans to have sludge samples obtained from four different power plants conditioned by at least two commercial processes. Testing of the treated samples is being performed by Aerospace to determine the following characteristics:

1. Soluble components.

2. Permeability.

3. Water retention.

4. Compression strength.

5. Bulk density.

6. Detoxification assessment, if appropriate.

The work includes sampling from TVA's Shawnee Plant and from SCE's Mohave Station. Also to be included are sludges from a lime scrubbing system and from a double alkali system.

A field study of sludge disposal is planned at TVA's Shawnee Plant under EPA sponsorship where the Chemfix, IUCS, and Dravo processes will be evaluated.

1.3 Sludge Handling

The handling operations involved in disposing of treated sludge in landfills may include one or more of the following: wet sluicing (or piping) of sludge, additives, and/or fly ash; trucking of ash and other fixation additives; trucking of sludge to landfill site; use of conveyor belts for sludge transport between dewatering, treating, landfilling, and/or trucking facilities; barging; and rail transport. The first of these potential operations has been discussed in Section II-C. Each of the others is briefly described below with emphasis placed on any aspects associated with sulfur oxide scrubber sludge.

Transport of sludge to a landfill site via truck is one of the approaches being considered by utilities if off-site disposal is used. Combustion Engineering transported 8[illegible] metric tons of waste sludge from the limestone scrubber at Kansas Power and Light's Lawrence facility to Dulles Airport in Washington, D.C., a distance of approximately 2100 km (1305 miles). Two types of vehicles, flat- and round-bottomed trucks, were employed in order to compare the effect of various features on handling characteristics. Prior to loading, the untreated sludge had been stored in a settling pond at the utility site for 6 months. It was dredged up and allowed to drain for 24 hours before loading. At various intervals during the nonstop trip measurements and samples were taken. No leakage of sludge was observed although excess water drained from the tailgate while on the road. Unloading difficulties were encountered with the flat-bottomed trucks; complete removal of the sludge necessitated manipulation with a backhoe. The sludge slid out readily, however, from the round-bottomed trailers.

Experience with trucking of sludge from Duquesne Light Company's Phillips Station has indicated successful operation with sludge treated with Dravo's additive. A spokesman for Dravo Corporation recently pointed out the fact that trucking sludge from a large power plant would not be practical, however, as it would require 40 truck loads per hour to dispose of the sludge (Ref. 30). With this fact in mind, Dravo is currently testing the possibility of piping a 30-35 percent solids slurry containing fixation additives to an off-site landfill.

The costs associated with truck transport of sludge are dependent upon wage rates, distance, load limits, and cycle times. Figure II-4 depicts typical haul rates of stabilized material based on the use of 20-ton trucks (Ref. 50).

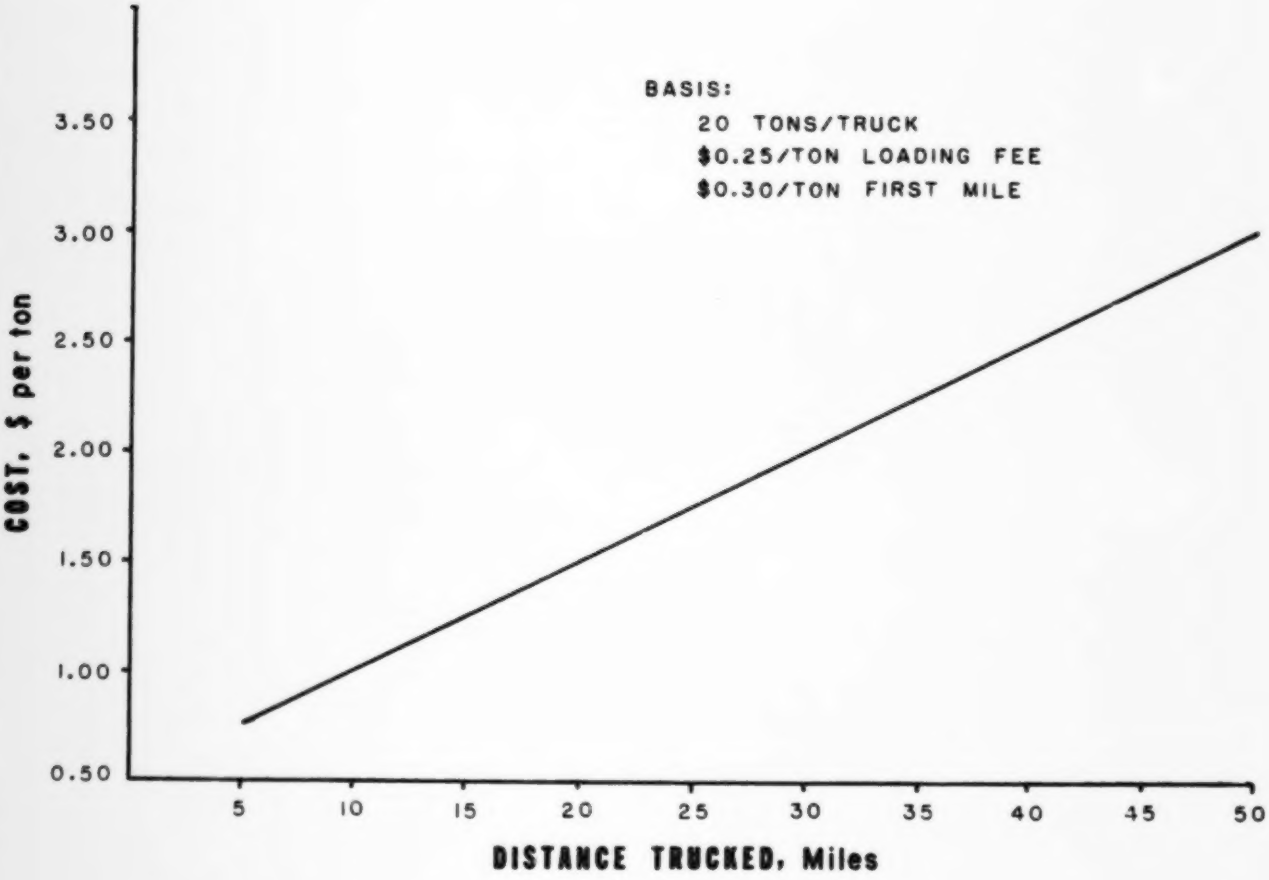

Figure II-4. Typical Hauling Rates for Stabilized Fly Ash Compositions (Ref. 50).

One source, in comparing the economics of piping versus truck transport, stated that 80 kilometers (about 50 miles) should be considered the cut-off distance. For greater distances, piping appears more economically attractive (Ref. 29). This would vary, of course, depending upon the physical properties of the material to be transported.

Dravo has estimated that a typical 5 mile haul would cost about $0.05/ton mile

The rental for trucks is an expensive item. A spokesman for Commonwealth Edison cited $24.00 per hour for a 12 cubic yard ready-mix truck for use in mixing and hauling their stabilized sludge and $16.00 per hour for a 12 cubic yard dump truck (Ref. 18).

Conveyor belts and related bucket elevators are potential modes of transport for dewatered sludge over short distances. Potential areas of use include conveying of dewatered solids to a fixation facility, lifting of wastes to hoppers or mixing devices, and transport of fixed sludge to landfill sites. The water content of the sludge is the major factor determining feasibility of this application. If the nature of the sludge is such that water drains in large amounts, precautions such as installation of troughs below the conveyors must be taken to avoid potential water pollution problems.

Other alternate methods of transporting the waste from the scrubber site to the ultimate disposal site include barge and rail. Both would be feasible where geography and surrounding environment would permit such application.

Barge transportation of sludge, while only feasible for utilities near navigable waterways, is economically attractive.

The cost for transporting sludge on ordinary barges exclusive of costs for unloading and loading facilities appears to be about $0.01 per wet ton mile (Ref. 30).

For volumes below about 100 cubic meters (26,000 gallons) per day, trucking or rail becomes more economically attractive (Ref. 51). In this case distance should be the basis for selection: trucks for distances shorter than 80 km (50 miles) and railways or barges for longer distances.

2.0 Water Pollution Aspects of Landfill Disposal

In order to predict leachate characterisitcs of a landfill, it is first necessary to describe the general features of water movement and geological considerations for this disposal method. Due to this recent surge of ecological interest in sanitary landfills utilized for solid waste disposal, there is an abundance of information available. Emrich's review of research in this field presents an overall view of progress in the following areas (Ref. 52):

1. Leachate generation.
2. Chemical characteristics of leachate.
3. Movement of water in a landfill.
4. Effects of topography, geology, soil, and groundwater on leachate.
5. Leachate or landfill management.

This section will present a discussion of landfill leachate in general with specific reference to formation, nature, and movement of leachate generated by lime/limestone scrubber wastes.

The first consideration when looking at the potential impact of landfill leachate is the volume of leachate which will be produced. This is a direct function of the amount of water reaching the landfill. There are two possible sources of this water: rainfall and naturally occurring subsurface flow through the landfill site. This second situation occurs when the landfill extends below the existing water table. Climate obviously will determine the rainfall. In humid areas leachate will be generated in a relatively short period of time; however, leachate formation may be delayed for years until field capacity is reached in semiarid and arid regions (Ref. 52). In general, the field capacity of a landfill is the water that can be retained indefinitely against gravitational force.

Subsurface flow is a natural phenomenon which can seriously interfere with safe operation of landfills in two ways. First, it is a source of additional volume of potentially harmful leachate. The second consideration is that it can serve as a direct means of groundwater contamination. Prevention can be effected by thorough geologic study of the site beforehand and, if needed, installation of rerouting devices for the groundwater flow.

In a similar vein, coverage of the landfill area when complete will greatly reduce, if not eliminate, the amount of leachate produced; this aspect is discussed in Subsection II-D-2.2.

Infiltration and permeability characteristics of landfill material determine the relative amounts of runoff versus leachate as well as the leaching rate. Minnick has looked at the effect of aging on permeability of fly ash stabilized with lime (Poz-O-Pac®) and fly ash stabilized with sulfur oxide sludges in addition to lime (Poz-O-Tec) (Ref. 9). As shown in Figure II-5, a great reduction in permeability of fly ash mixtures is reported by inclusion of sulfur oxide sludges. In terms of the subject of this report, these results indicate not only the low permeability values of the fixed scrubber sludges ($\sim 10^{-7}$ cm/sec after 7 days of curing at 38°C (100°F)), but also the relatively great reduction in permeability compared to freshly prepared sludge/fly ash mixtures. This reduction is on the order of 2 orders of magnitude. More specific data obtained with samples of sludge stabilized by IU Conversion System's process is presented in Table II-11. These data were measured using standard falling head permeability procedures.

Table II-12 presents IUCS data for Shawnee limestone sludge. Falling head permeability data indicate improvement during the first month of curing from 10^{-4} to 10^{-6} cm/sec.

Dravo Corporation reportedly has obtained permeability values ranging from 1×10^{-4} cm/sec for remolded material to 1×10^{-8} cm/sec for undisturbed material (Ref. 47). This is compared to high quality clays having permeation values of 10^{-7} to 10^{-8} cm/sec and fly ash for which a representative range is 10^{-2} to 10^{-3} cm/sec.

Leaching experiments have been performed on various sludges and processed materials to help in evaluating the water quality threat from sludge disposal. Procedures for leaching experiments will not simulate environmental conditions; the laboratory conditions are worse than those anticipated in field applications and should represent a "worst case" example.

Minnick has presented analytical results obtained by atomic absorption analysis of leachable ions on selected

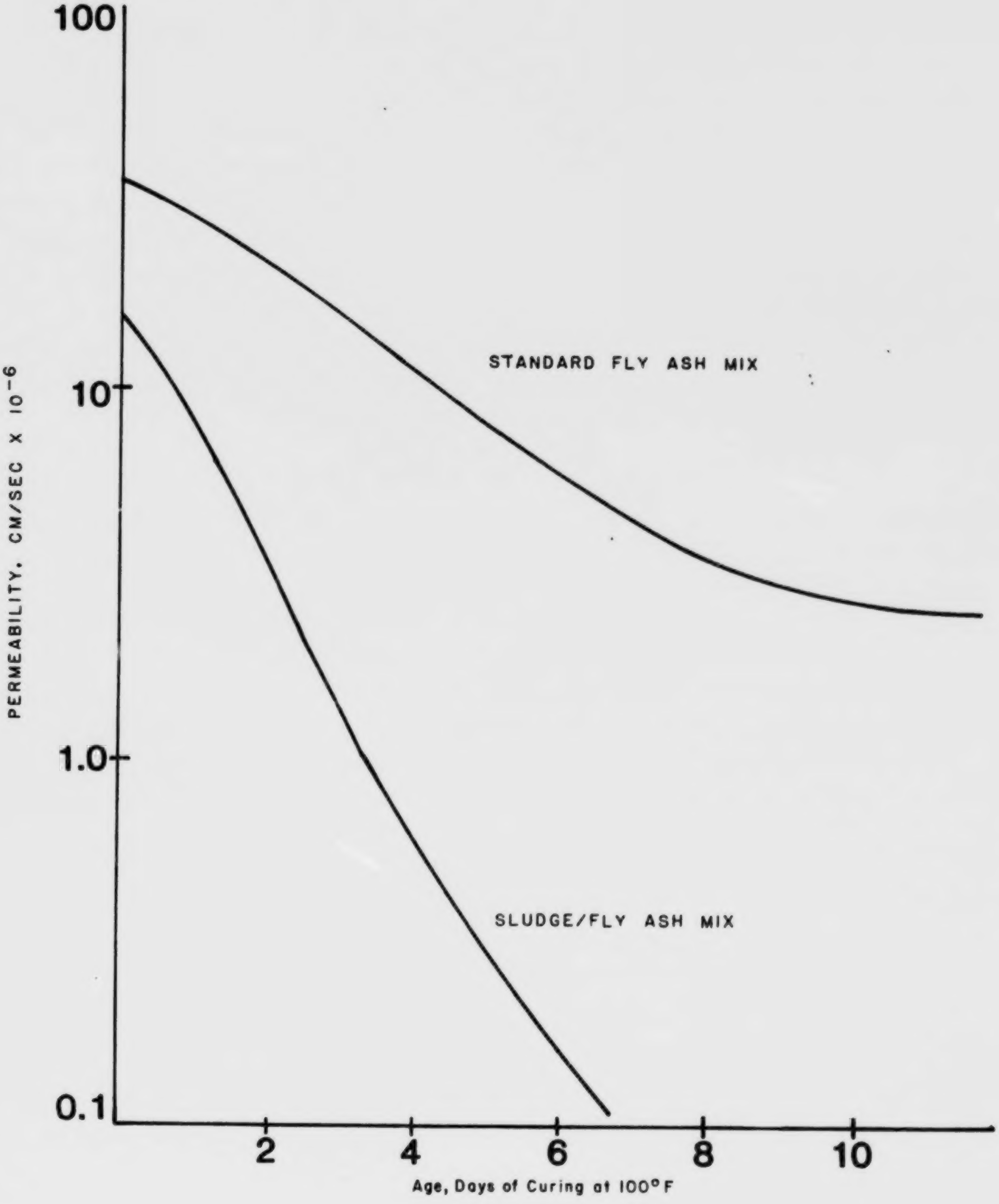

Figure II-5. Comparison of Poz-O-Pac and Poz-O-Tec Permeability Values.

Table II-11. RESULTS OF TESTS OF SELECTED STABILIZED ROAD BASE MIXTURES PREPARED AT DULLES AIRPORT TRANSPO 72 PROJECT[a]

Moisture Content, %	Dry Density, pcf[b]	7-Day Falling Head Permeabilities, cm/sec
19.4	98.8	2.4×10^{-6}
19.4	98.1	N.D.[c]
20.0	98.3	2.9×10^{-6}
19.8	98.2	6.5×10^{-6}
19.7	100.6	5.7×10^{-6}
20.0	98.8	1.0×10^{-6}
19.1	100.4	N.D.

[a] Ref. 9

[b] One pcf is equivalent to 16,028 g per cubic meter.

[c] N.D. - Not Determined

Table II-12. LABORATORY RESULTS OF FIXED TVA LIMESTONE SLUDGE ANALYSIS[a]

LEACHATE CONCENTRATIONS, ppm[b]	AGE OF TEST, days					
	2	4	6	10	14	28
Total Alkali	1068	542	810	524	40	40
Tot. Dis. Solids	1370	730	1210	770	180	250
SO_3	11	19	14	20	10	3
SO_4	45.2	41.9	36.2	51.0	48.5	43.6
Cl	64	12	74	21	16	14
Ca	268	220	235	170	27.5	20
Mg	0.005	0.005	0.005	0.01	--	--
Al	2.2	3.2	11.4	0.95	0.05	0.1
Fe	0.02	0.01	0.01	0.05	0.01	<0.01
Mn	0.005	0.01	0.007	0.007	0.005	<0.005
Cu	0.02	0.01	0.01	0.02	0.005	<0.01
Zn	0.005	0.01	0.005	0.005	0.005	<0.005
Cd	0.007	0.005	0.005	0.005	0.005	<0.005
Cr^{+3}	0.05	0.03	0.02	0.02	0.01	<0.01
As	0.01	0.01	--	--	--	--
Pb	0.2	0.05	0.05	0.05	0.05	<0.03
Sn	0.1	0.1	0.05	0.05	0.05	<0.1
Hg	0.01	0.01	--	--	--	--
pH	12.35	12.5	12.1	11.9	10.2	9.0

	AGE OF TEST, days				
	0	7	14	21	35
PERMEABILITY, cm/sec	1×10^{-4}	6.5×10^{-5}	--	6.2×10^{-6}	5.0×10^{-6}
COMPRESSIVE STRENGTH, tons/sq ft	--	4.1	4.7	--	--

[a] Ref. 32

[b] Equivalent to mg/l

materials subjected to the Poz-O-Tec or Poz-O-Pac® process (Ref. 9). The tests were conducted by shaking 500 gram test specimens for 48 hours in 2 liters of distilled water. The results of those studies are shown in Table II-13. When leachate from materials treated by the Poz-O-Tec process were compared to federal specifications for drinking water standards, only manganese greatly exceeded the limits. It was noted that materials not treated by either stabilization process experienced much greater leaching phenomena, thus indicating the effectiveness of this type of chemical fixation. In Table II-13 the decrease in total dissolved solids with aging for the Dulles cylinder is noteworthy. An IUCS analysis of leachate from the fixed Shawnee limestone scrubber sludge is given in Table II-12. The data show decreased concentrations with time.

An analysis of a sludge stabilized by the Dravo process is given in Table II-14 for comparison to the other leachate analyses.

The Chemfix process has recently been tested on a sludge sample from an Eastern coal burning power plant controlled by a limestone scrubbing system (Ref. 53). Analyses of the raw untreated sludge and leachate from the fixed sample were performed. The results as shown in Tables II-15 and II-16 indicate that the concentrations of reported toxic elements and ions were reduced in most cases to less than 0.10 ppm. Copper and lead concentrations also decreased to this value after the first leachate portion. Analysis of chloride was not given. There have been reports that Chemfix solids have not retained chlorides, cyanide, and hexavalent chromium. These elements may be problem areas (Ref. 54).

Table II-13. ATOMIC ABSORPTION TESTS FOR LEACHABLE IONS ON SELECTED SPECIMENS SUBJECTED TO 48 HOUR SHAKING TEST[a]

		Concentration, ppm													
	pH	Total Dissolved Solids	Sulfate	Cl	Al	Total Iron	Mn	Cu	Zn	Cd	Cr+3	As	Hg	Pb	Sn
FEDERAL SPECIFICATIONS - MAX[b]		500	250	250	None	0.3	0.05	1.0	5.0	0.01	0.05	0.01	0.001	0.05	None
Individual Solid Specimen															
Dulles Cylinder (13 Days)	9.5	840	100	8	0.38	0.08	0.18	0.08	0.02	<0.01	0.02	0.02	<0.001	0.08	0.10
Dulles Cylinder (22 Days)	9.5	620	120	12	0.37	0.08	0.16	0.08	<0.01	<0.01	<0.01	0.02	<0.001	0.09	0.10
Poz-O-Tec Test Road Core	6.7	90	16	14	0.03	0.06	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01
Poz-O-Tec Test Road Cylinder	9.2	250	136	16	0.05	0.10	0.10	0.08	<0.01	<0.01	<0.01	0.01	<0.001	0.01	<0.01
Poz-O-Pac Cylinder	9.3	150	44	26	0.10	0.25	<0.05	0.08	<0.01	<0.01	<0.01	0.01	<0.001	0.02	<0.01
Fly Ash Concrete	10.7	440	170	46	0.22	0.01	<0.05	0.04	<0.01	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01
Cinder Block	8.2	410	60	6	0.01	0.04	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	0.02	<0.01
Clay Brick	7.3	110	28	12	0.03	0.10	<0.05	0.01	<0.01	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01
Asphalt Roofing Shingle	7.1	150	46	22	0.01	0.12	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01
Aggregate															
Argillite	6.9	120	28	22	0.07	0.06	<0.05	0.08	<0.01	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01
Dolomitic Limestone	9 75	96	8	18	0.02	0.36	<0.05	<0.01	0.02	<0.01	<0.01	<0.01	<0.001	0.07	<0.5
Calcitic Limestone	8.4	180	8	-	0.02	1.8	<0.05	<0.01	0.04	<0.01	<0.01	<0.01	<0.001	0.03	<0.5
Steel Slag Aggregate	10.8	840	16	28	0.05	0.15	<0.05	<0.01	0.02	0.01	<0.01	<0.01	<0.001	0.01	<0.05
Pumice	7.1	120	< 1	10	0.06	2.2	<0.05	<0.01	0.03	<0.01	<0.01	<0.01	<0.001	0.06	<0.05
Fly Ash Sludge Aggregate	11.7	700	< 1	16	0.03	0.26	<0.05	<0.01	0.02	<0.01	<0.01	<0.01	<0.001	0.06	0.5
Cement Mortar Balls	9.0	530	27	8	0.04	0.17	<0.05	<0.01	0.01	<0.01	<0.01	<0.01	<0.001	0.03	<0.01
Mine Tailings	3.95	130	6	2	0.05	0.15	<0.05	0.16	0.02	<0.01	<0.01	<0.01	<0.001	0.07	<0.05
Loose Powdered Materials															
Fly Ash	9.8	2900	1500	8	0.11	0.26	<0.05	<0.01	0.01	<0.01	<0.01	<0.01	<0.001	0.06	<0.5
Portland Cement	12.0	3700	200	20	0.05	0.44	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	0.04	<0.5
Water Samples															
Tap Water	7.5	180	36	76	0.02	<0.01	<0.05	0.08	0.05	<0.01	<0.01	<0.01	<0.001	0.04	<0.01
Snow Sample from Pittsburgh	6.45	40	< 1	6	0.06	0.46	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.001	0.02	<0.01
Water Supply (Peggs Creek)	7.25	316	-	-	-	2.9	<0.05	0.05	0.02	<0.01	<0.01	<0.01	<0.001	0.02	<0.01

[a] Ref. 9.

[b] Public Health Service Drinking Water Standards.

Table II-14. CHEMICAL CONSTITUENTS OF STABILIZED DESULFURIZATION SYSTEM SLUDGE LEACHATE[a,b]

Constituent	Concentration, mg/l
pH	11.6
Dissolved salts	590
Dissolved SiO_2	N.D.[c]
Hardness, $CaCO_3$	430
Fe++	N.D.[c]
Total iron	N.D.[c]
Ca++	172
Mg++	0.05
Mn++	0.03
Na+	4
Al+++	4
Alkalinity as $CaCO_3$	140
Cl^-	66
$SO_4^=$	100
$SO_3^=$	92
$PO_4^=$	N.D.[c]

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[a] Ref. 47

[b] In this leachate analysis, the pH is high but all other criteria are within the range of regulatory requirements.

[c] N.D. - Not detectable.

Table II-15. CHEMFIX PRELIMINARY LEACHING STUDY
LAB LEACHATE OF 2/28/73 FIELD CHEMFIX PRODUCE
ILLINOIS POWER PLANT[a,b]

Constituent	Raw Sludge[c]	Leachate Water[d]				PHS Drinking Water Standards (Added for reference)
		25	50	75	100	
Aluminum (Al)	1.2	<0.10	< 0.10	<0.10	< 0.10	--
Cadmium (Cd)	1.1	<0.10	< 0.10	<0.10	< 0.10	0.01
Total Chromium (Cr)	0.8	<0.10	< 0.10	<0.10	< 0.10	0.05
Copper (Cu)	9.0	<0.25	< 0.10	<0.10	< 0.10	1.0
Cyanide (CN^-)	< 0.10	<0.10	< 0.10	<0.10	< 0.10	0.01
Iron (Fe)	760	<0.10	< 0.10	<0.10	< 0.10	0.3
Lead (Pb)	3.7	<0.25	< 0.10	<0.10	< 0.10	0.05
Nickel (Ni)	11	<0.10	< 0.10	<0.10	< 0.10	--
Phenol	0.25	<0.10	< 0.10	<0.10	< 0.10	0.001
Zinc (Zn)	29	<0.10	< 0.10	<0.10	< 0.10	5.0

[a] Ref. 48

[b] All results in ppm, unless otherwise indicated

[c] Sludge sample from full scale limestone scrubbing system at Commonwealth Edison's Will County Station. Composite material from three disposal cells.

[d] Each 25 in. of leachate water represents approximately 800 cc of water.

Table II-16. CHEMFIX PRELIMINARY LEACHING STUDY, LAB LEACHATE OF 9/14/73 LAB CHEMFIX PRODUCT[a,b]

Constituent	Raw Sludge[c]	Leachate Water[d]	PHS Drinking Water Standards (Added for Reference)
Arsenic (As)	2.2	<0.10	0.01
Cadmium (Cd)	0.30	<0.10	0.01
Chloride (Cl^-)	--	64	250
Total Chromium (Cr)	2.8	<0.25	0.05
Copper	1.5	<0.10	1.0
Cyanide (CN^-)	<0.10	<0.10	0.01
Iron (Fe)	120	$<$ 0.10	0.3
Lead (Pb)	26	$<$ 0.10	0.05
Mercury (Hg)	<0.10	$<$ 0.10	--
Nickel (Ni)	3.5	$<$ 0.10	--
Phenol	<0.25	$<$ 0.10	0.001
Sulfate ($SO_4{=}$)	$>$ 10,000	400	250
Zinc (Zn)	16	$<$ 0.10	5.0

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[a] Ref. 55

[b] All results in ppm

[c] Sludge sample from a turbulent contact absorber scrubber on a prototype unit (10 Mw) in partially closed loop operation at the TVA Shawnee Power Plant.

[d] Each 25 in. of leachate represents approximately 800 cc of distilled water.

Joseph Bern from U. S. Utilities Service Corporation presented leaching test results from 25 sludge samples generated by lime wet scrubber pilot plant operations at Duquesne Light Company, Phillips Station, and Ohio Edison Company's Burger Station. The samples included raw sludge, treated sludges, and processed sludges suitable for use as aggregate. These data are given in Tables II-17 through II-21.

Table II-17 shows the chemical analyses of sludge samples S-1 through S-6. The leachates from the sludge samples are included in Table II-18 and are identified as L-1 through L-6.

Leaching test results for a dewatered and sintered sludge product are included in Table II-19. The samples are designated as L-7A, L-8A, and L-9A.

Table II-20 lists the results from analyses of samples L-11 through L-20. Leaching experiments were performed on three processed sludges of different lime compositions to generate this data. In addition, each sample was aged and the analyses were repeated to show the effect of aging on the leaching characteristics of the processed material. Table II-21 contains more chemical information concerning leachates from sludges which contain varying amounts of proprietary additive.

An examination of the data indicates that solubilities of heavy metal ions appear to be an inverse function of the pH. The data also indicate concentrations of heavy metal ions below the detection limit or effluent standards in most cases.

Table II-17. SLUDGE ANALYSIS [a]

Parameters	Penn DER W.Q. Criteria Regulations - Chapt. 93	Orsanco Pollution Control Standard 1-70 & 2-70	U.S.P.H.S. Drinking Water Standards	Sludge Analysis					
				S-1	S-2	S-3	S-4	S-5	S-6
pH	6-8.5								
Total Dissolved Solids (TDS)	750 max. (once) 500 max.(mo ave.)								
Alkalinity	20 avg (not less)								
Sulfate (SO_4)	250		250						
Total Iron (Fe)	1.5		0.3	1340	1840	2640	3740	3949	525
Copper (Cu)	0.10		1.0	2.94	3.71	5.12	6.53	0.89	0.15
Zinc (Zn)	0.05		5.0	7.07	9.96	12.26	13.98	55.0	55.0
Chromium (Cr)		0.05	0.05	10.0	14.7	9.13	10.86	16.67	3.33
Lead (Pb)		0.05	0.05	0.97	0.94	1.38	2.95	3.70	0.05
Cadmium (Cd)		0.01	0.01	0.32	0.32	0.34	0.26	0.02	0.01
Mercury (Hg)		0.005	0.005	3.50	4.20	3.80	3.10	0.18	4 ppb
Manganese (Mn)	1.0		0.05						20.9
Arsenic (As)		0.05	0.01						

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[a] Ref. 56

Table II-18. LEACHATE ANALYSES FROM SLUDGE SAMPLES S-1 THROUGH S-6[a]

Parameter	L-1	L-2	L-3	L-4	L-5	L-6
pH	7.8	7.7	7.9	8.6	11.6	11.7
Total Dissolved Solids (TDS)						
Alkalinity	70.0	60.0	55.0	48.0	26	220
Sulfate (SO_4)	1783[b]	1547[b]	1731[b]	1049[b]	1400[b]	1430[b]
Total Iron (Fe)	0.04	0.08	0.06	0.02	0.02	0.04
Copper (Cu)	<0.02	0.02	0.02	0.02	0.02	0.02
Zinc (Zn)	0.15[b]	0.18[b]	0.04	<0.01	<0.01	<0.01
Chromium (Cr)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Lead (Pb)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cadmium (Cd)	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Mercury (Hg)	<0.001	<0.001	<0.001	<0.001	<1 ppb	<1 ppb
Manganese (Mn)					<0.02	<0.02
Arsenic (As)						

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[a] Ref. 56.

[b] Exceeds stream criteria.

Table II-19. LEACHATE ANALYSES FROM COMMERCIAL PRODUCT (SINTERED OR ROASTED DEWATERED SLUDGE)[a]

Parameter	L-7A	L-8A	L-9A
pH	9.5	8.5	9.2
TDS	620	840[b]	250
Alkalinity	350	470	34
Sulfate (SO_4)	120	108	136
Total Iron (Fe)	0.081	0.08	0.10
Copper (Cu)	0.08	0.08	0.08
Zinc (Zn)	<0.01	0.02	<0.01
Chromium (Cr)	<0.01	0.02	0.01
Lead (Pb)	0.03	0.09[b]	0.01
Cadmium (Cd)	<0.01	<0.01	<0.01
Mercury (Hg)	<0.001	<0.001	<0.001
Manganese (Mn)	0.80	0.10	0.10
Arsenic (As)	0.02	0.02	0.01

[a] Ref. 56.

[b] Exceeds stream criteria.

Table II-20. LEACHATE ANALYSES FROM COMMERCIAL PRODUCT (SINTERED OR ROASTED DEWATERED SLUDGE) DIFFERENT LIME COMPOSITION [a]

	Penn DER Anal-ysis	Sample 1[b]				Sample 2[b]			Sample 3[b]		
		1 day	7 days	14 days	44 days	1 day	7 days	14 days	1 day	7 days	14 days
Parameter	L-10	L-11	L-12	L-13	L-14	L-15	L-16	L-17	L-18	L-19	L-20
pH	10.25	11.5	11.4	11.0	10.8	11.4	11.3	10.9	11.8	11.7	9.6
TDS		692	520	450	396	595	480	432	961	825	621
Alkalinity		536	470	334	222	960	444	210	1260		
Sulfate (SO_4)	929[c]	6	20		52	80	24	54	60	24	200
Tot. Iron (Fe)	0.07	0.10	0.15	0.12	0.12	0.14	0.08	0.35	0.06	0.13	0.13
Copper (Cu)		0.08	0.16[c]	< 0.01	0.04	< 0.01	0.04	< 0.01	0.08	0.16[c]	< 0.01
Zinc (Zn)	< 0.01	< 0.01	< 0.01	0.03	< 0.01	0.02	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Chromium (Cr)		< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Lead (Pb)	0.15	0.02	0.05	0.05	0.02	0.03	0.05	0.05	0.03	0.07	0.02
Cadmium (Cd)	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mercury (Hg)	< 1 ppb	< 0.001	0.002	< 0.001	0.004	0.004	0.001	0.001	0.003	0.001	0.002
Manganese (Mn)		< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	< 0.05	< 0.05	< 0.05	< 0.05
Arsenic (As)		< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

[a] Ref. 56

[b] Samples were made from different lime mixtures during the pilot plant operations.

[c] Exceeds stream criteria.

Table II-21. PILOT PLANT SLUDGE WITH DIFFERENT QUANTITIES OF HARDENING ADDITIVE[a,b]

Parameter	L-21	L-22	L-23	L-24	L-25
pH	7.9	11.0	11.0	7.9	9.7
TDS	1168[c]	900[c]	924[c]	1148[c]	920[c]
Sulfate (SO_4)	731[c]	468[c]	551[c]	740[c]	490[c]
Total Iron (Fe)	0.13	0.10	0.10	0.10	0.10
Copper (Cu)	<0.10	<0.10	<0.10	<0.10	<0.10
Zinc (Zn)	0.02	0.02	0.02	0.02	0.02
Chromium (Cr)	<0.20	<0.20	<0.20	<0.20	<0.20
Lead (Pb)	0.01	0.01	0.01	0.01	<0.01
Cadmium (Cd)	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury (Hg)	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Manganese (Mn)	<0.05	<0.05	<0.05	<0.05	<0.05
Arsenic (As)	0.085[c]	0.05	0.01	0.035	0.045

[a] Ref. 56.

[b] Plant operated with varying stoichiometric ratios of slaked lime.

[c] Exceeds stream criteria.

The aging experiments showed an increase in dissolved solids and sulfates in the sintered processed sludge.

2.1 Runoff Considerations

IU Conversion Systems has performed tests to determine the extent of dissolution of species associated with fly ash-stabilized sulfur oxide sludges (Ref. 9). The experiments were conducted by allowing 2 liters of deionized water to flow over the fixed samples and then subsequently collected. Results of atomic absorption analyses of this runoff were reported as shown in Table II-22. They were interpreted as providing a preliminary basis for the effectiveness of the fixation process's ability to tie up soluble species within the lattice complexes.

Table II-23 contains run-off analyses reported by Joseph Bern (Ref. 56). The samples were generated by dripping 2000 ml of deionized and distilled water on the sintered and processed sludge at 1 ml per second. The water was collected, filtered, and analyzed.

2.2 Preventive Measures

In cases where fixation processes are economically undesirable, it may become necessary to examine other alternatives to prevent water pollution. Methods available to prevent contamination of surface and groundwaters include landfill sealing, coverage, and provision of drainage to divert naturally occurring surface or groundwater flows around the landfill.

Interception of subsurface flow is achieved by placement of drains upstream of the entire area of the landfill.

Table II-22. ATOMIC ABSORPTION TESTS MADE ON SURFACE RUNOFF OF A STABILIZED FLY ASH/SLUDGE MIXTURE[a,b]

Parameter	Dulles Cylinder (13 Days)	Dulles Cylinder (23 Days)	Sulfite Beam
pH	7.0	6.9	7.2
Total Dissolved Solids	100	96	85
Sulfate	26	32	8
Cl	12	18	18
Al	0.10	0.15	0.13
Total Iron	0.22	0.06	0.06
Mn	< 0.05	< 0.05	0.60
Cu	< 0.01	< 0.01	0.12
Zn	< 0.01	< 0.01	< 0.01
Cd	< 0.01	< 0.01	< 0.01
Cr^{+3}	< 0.01	< 0.01	< 0.01
As	< 0.01	< 0.01	< 0.01
Hg	< 0.001	< 0.001	< 0.001
Pb	< 0.01	< 0.01	0.03
Sn	< 0.01	< 0.01	< 0.01

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[a] Ref. 9

[b] With the exception of pH, all values are reported in parts per million

Table II-23. RUNOFF ANALYSES FROM SINTERED PROCESSED SLUDGE[a,b]

Parameter	L-7	L-8	L-9
pH	6.9	7.0	6.7
TDS	96	100	90
Alkalinity	20	14[b]	10[b]
Sulfate (SO_4)	32	26	16
Tot. Iron (Fe)	0.06	0.22	0.06
Copper (Cu)	< 0.01	< 0.01	< 0.01
Zinc (Zn)	< 0.01	< 0.01	< 0.01
Chromium (Cr)	< 0.01	< 0.01	< 0.01
Lead (Pb)	< 0.01	< 0.01	< 0.01
Cadmium (Cd)	< 0.01	< 0.01	< 0.01
Mercury (Hg)	< 0.001	< 0.001	< 0.001
Manganese (Mn)	< 0.05	< 0.05	< 0.05
Arsenic (As)	< 0.01	< 0.01	< 0.01

[a] Ref. 56

[b] Exceeds stream criteria

These cut-off drains should be placed at a depth a few meters below the bottom of the landfill to keep the groundwater level low as well as to provide hydraulic gradient for drainage (Ref. 57).

To prevent infiltration from surface flow, two approaches can be taken. One involves providing vertical gravel or stone paths extending below the level of the bottom of the landfill through which surface and/or groundwater can quickly drain. The second approach involves using a cover material. This may be a natural material, such as clay or clay loam, or an artificial membrane. If an impermeable cover is employed, precaution must be taken to allow release of gases to the atmosphere. In some instances, carbon dioxide produced in a landfill has been observed to contaminate groundwater with additional hardness.

Landfill sealing is very similar to the practice of pond sealing discussed in Section II-C. The sealant can be any impermeable material such as an asphalt membrane recently tested at a site near Tullytown, Pennsylvania (Refs. 58, 59). Many other potential lining materials have been tested in bench-scale and experimental plot arrangements. A few of the more promising of those tested included:

1. 10 percent bentonite (Wyoming clay used for mud drilling)/ 90 percent soil.

2. 10 percent bentonite/90 percent sand.

3. 10 percent red mud slurry (a bauxite residue)/ 90 percent soil.

4. 10 percent latex/90 percent soil.

5. 30 percent asphalt emulsion/70 percent soil.

A study was performed to test the feasibility of using latex as a soil sealant to prevent acid mine drainage seepage into subterranean abandoned mines (Ref. 60). Initially, a variety of latexes were screened in laboratory tests using reconstructed soil columns. The most promising latex, a styrene-butadiene rubber (SBR) latex, was then tested on selected quarter acre field plots. In general, the field tests confirmed that latex does reduce the permeability of soil to water. However, the economics are not attractive and most of the latex is deposited in the top foot of soil where it is subject to damage by microbiological attack, frost, and surface vegetation.

In an arrangement where a landfill liner is used, the leachate is trapped at the bottom. It can then be collected and subjected to water treatment, if necessary, before release to the surrounding area.

3.0 Land Reclamation Aspects of Disposal Sites

Certain aspects of land reclamation following abandonment of a landfill site or filled pond used for scrubber sludges may lead to potential problems. These aspects may be assessed by examining the engineering, physical, and chemical natures of treated and untreated sludge.

3.1 Moisture Content and Rewatering Characteristics

One consideration is the tendency of dried scrubber sludge to absorb water that it contacts. As discussed in previous sections of this report, sulfur oxide sludges are relatively difficult to dewater. One sludge sample was observed over a period of several months during which time little or no settling took place after the first 48 hours. Drainability studies conducted by Aerospace resulted in retention of enough water by dried Shawnee limestone sludge to return to its original water content. The calculated water retention for sludge with underdrainage was 51.7 percent (Ref. 38). Behavior of chemically stabilized sludge samples is expected to be greatly improved although specific tests for rewatering potential have not been reported. A practical consideration in regard to rewatering is that for a thick layer of dewatered sludge, an accumulation of a few feet of rain might be required for rewatering. With proper design of the site plus some low permeability cover material (clay, plastic, or treated sludge) even untreated sludge might never rewater since the small amount of water collected during a rain should be lost by evaporation before the next rain.

Untreated sludge disposed of in lined ponds may present serious land reclamation problems. The evaporative water loss, the only mechanism for dewatering in lined ponds, will be prohibited or greatly reduced in those parts of the country where annual precipitation approaches or exceeds annual evaporation. These problems could be avoided by chemical fixation.

Initial water content and general index properties of chemically fixed sludges will vary widely from test to test as well as from process to process. Dry densities of undisturbed Dravo-stabilized sludges reportedly ranged from 530.5 Kg/m^3 (33.1 lb/cu ft) to 700.4 Kg/m^3 (43.7 lb/cu ft). Water contents ranged from 42 percent solids to 48 percent solids (Ref. 47).

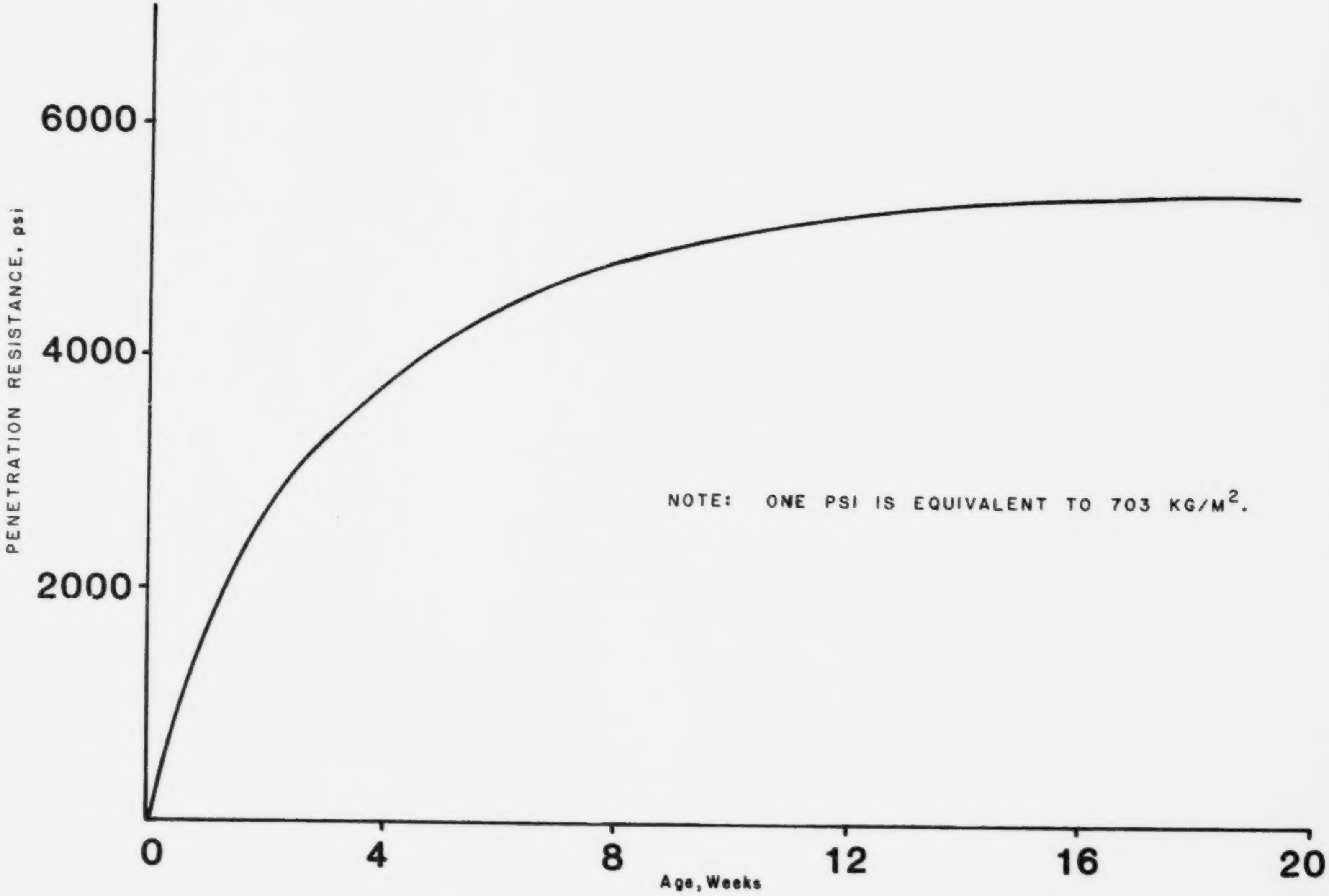
IUCS manufactures a substance from sludge which is suitable for road-building. Its moisture content is reported as 19.5-20 percent, and its dry density is 1570-1600 Kg/m^3 (98-100 lb/cu ft) (Ref. 10).

3.2 Strength of Disposed Material

A second consideration in land reclamation of sludge disposal areas is the weight which can be supported by the site. This factor can be determined by measuring the pozzolanic strength, compaction strength, and penetration resistance of the throwaway product. The strength associated with any landfill or construction material is a function of composition, moisture content, and compacted density.

Dried untreated scrubber sludge has been shown to be capable of supporting a load of 8 psi with water content below 35 percent based on studies performed by Aerospace on Shawnee and Mohave samples. This is deemed probably safe for equipment and personnel (Ref. 38). Neither sludge examined in this work showed any characteristics of pozzolanic strength which would lead to increased compressive strength. These tests have been described previously (Section I-E).

Samples subjected to the IU Conversion Systems fixation process have been tested for various strength characteristics (Ref. 9). The penetration resistance is a measure of the pressure that must be applied in kilograms per square meter to cause a penetration of 2.54 cm of a needle with cross-sectional area of 1.6 x 10^{-5} square meters. The effect of aging on the strength of a Sulf-O-Poz® composition was presented in graphical form (Figure II-6). The results indicate that completion of curing occurs approximately 16 weeks after mixing.



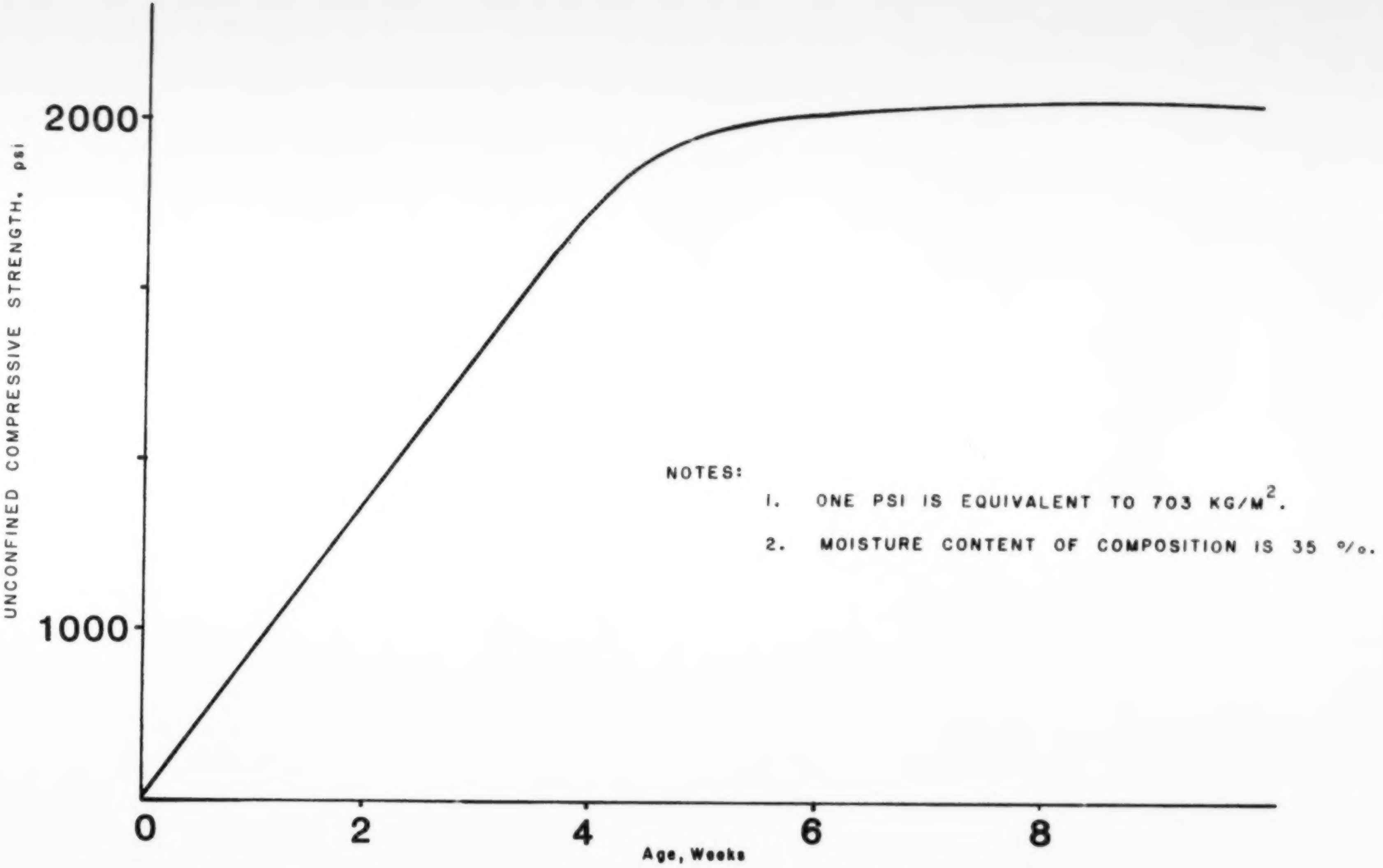
NOTE: ONE PSI IS EQUIVALENT TO 703 KG/M^2.

Figure II-6. Penetration Resistance for a Typical Fly Ash/Calcium Sulfate/Lime Mixture (Ref. 9).

When 5 x 5 x 5 centimeter cubes of similar composition were tested for unconfined compressive strength, curing was completed much sooner (~6 weeks). Graphical display of results is shown in Figure II-7. The moisture content of materials tested was 35 percent. Individual data points obtained during bench-scale compressive strength determinations of Sulf-O-Poz® materials with moisture contents of ~20 percent are shown in Table II-24. Table II-25 presents the results of compressive strength determinations for field-tested road base materials.

Dravo-stabilized sludges were subjected to direct shear and triaxial shear testing to develop strength parameters for embankment design and to evaluate bearing capacity. The angle of internal friction for undisturbed and remolded stabilized materials varied from 37 to 51 degrees; a typical value for a sludge cured for 30 days was 39 degrees. Untreated sludge exhibited an angle of internal friction between 27 and 30 degress. The strength of the stabilized sludge was comparable to that of dense sand and gravel under static loading conditions while the strength of the unstabilized sludge was similar to that of medium-dense sand. Figure II-8 compares the shearing strength of stabilized sludges to those of unstabilized sludges and sand. Figure II-9 shows the length of time required for development of the maximum strength for different amounts of additive. Although very little data is presently available on Chemfix treated scrubber sludges, a Chemfix spokesman reported that their experience has shown that treated industrial wastes, when cast in place, had better load bearing properties than wastes which had been dredged up and moved (Ref. 48).

In addition to strength, another consideration in an engineering evaluation is structural integrity. Experimental data which can be used to describe this characteristic are dimensional stability measurements and field testing.



NOTES:

1. ONE PSI IS EQUIVALENT TO 703 KG/M^2.
2. MOISTURE CONTENT OF COMPOSITION IS 35 %.

Figure II-7. Compressive Strength for a Typical Fly Ash/Calcium Sulfate/Lime Mixture (Ref. 9).

Table II-24. PHYSICAL PROPERTIES OF TRANSPO 72 BASE COURSE COMPOSITIONS[a]

Test Designation	Moisture Content %	Dry Density pcf[b]	Compressive Strength at 100°F (psi)[c]			California Bearing Ratio		Falling Head Permeabilities (cm/sec)
			2 Days	14 Days	28 Days	Immediate	28 Days	7 Days
2	19.5	98.8	301	732	881	52	543	2.4×10^{-6}
3	19.4	98.1	267	586	622	N.D.[d]	N.D.	N.D.
5	20.0	98.3	369	630	889	27	700	2.9×10^{-6}
6	19.8	98.2	196	458	490	20	460	6.5×10^{-6}
7	19.7	100.6	333	772	861	25	580	5.7×10^{-6}
9	20.0	98.8	290	761	789	90	644	1.0×10^{-6}
10	19.1	100.4	200	868	1091	N.D.	N.D.	N.D.

[a] Ref. 10

[b] One pcf is equivalent to 16,028 g/m^3

[c] One psi is equivalent to 703 kg/m^2

[d] N.D. - Not determined

Table II-25. RESULTS OF FIELD TESTS SHOWING COMPARISON OF POZ-O-PAC AND POZ-O-TEC FORMULATIONS[a]

Description	Dry Density pcf[b]	Compressive Strength at 100° F psi[c]		Strength of Core From Road[d], psi	
		2 Days	7 Days	4 Weeks	6 Weeks
Standard Fly Ash Mix (Poz-O-Pac)	121.2	66	770	NCP[e]	NCP
Fly Ash/Sludge Blend A (Poz-O-Tec)[f]	121.4	348	729	NCP	1034
Fly Ash/Sludge Blend B (Poz-O-Tec)[f]	120.8	318	746	756	1089

[a] Ref. 9

[b] One pcf is equivalent to 16,028 g/m^3

[c] One psi is equivalent to 703 kg/m^2

[d] Average temperature during curing period was 10°C

[e] NCP - No core possible due to insufficient strength

[f] Blends A and B not identified

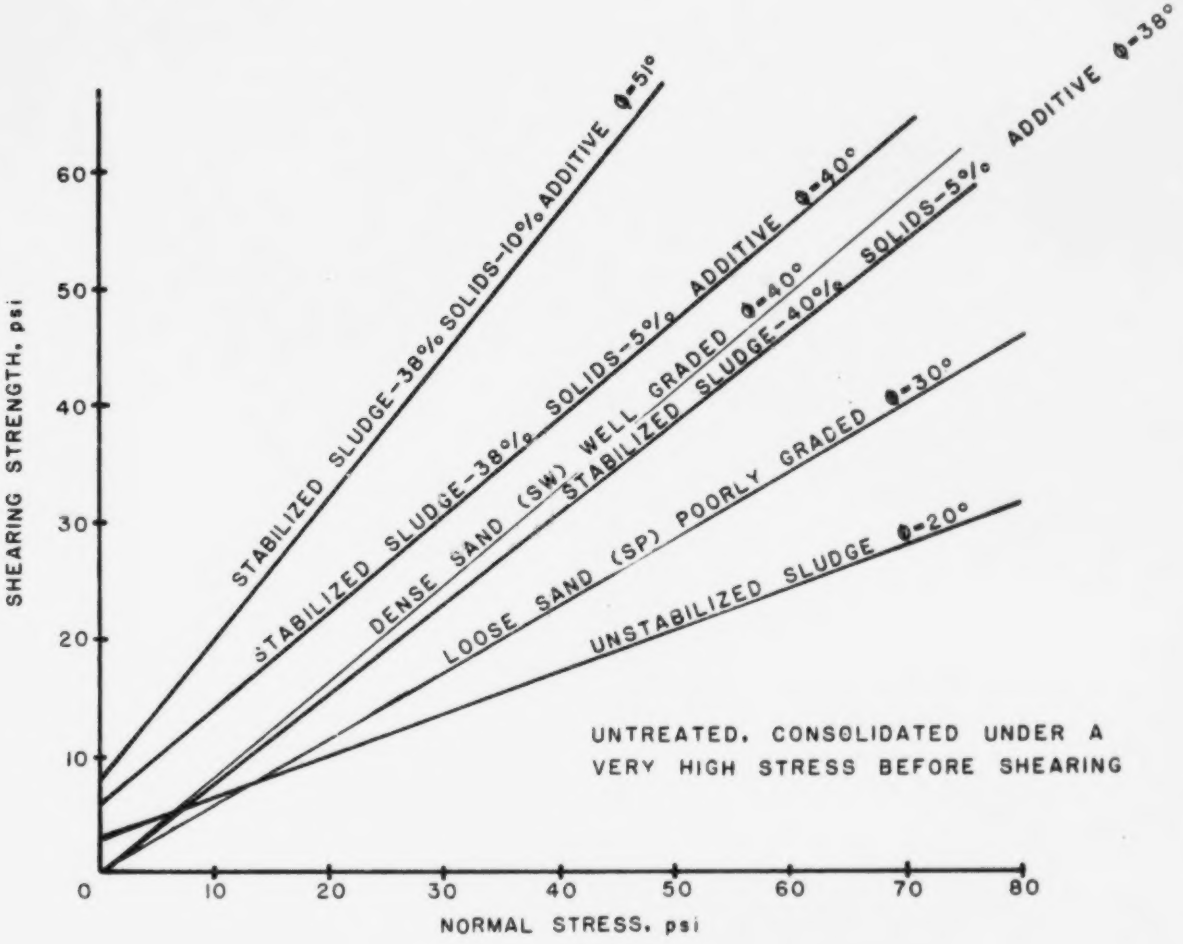


Figure II-8. Effect of Percent Dravo Additive on Shearing Strength (Ref. 47).

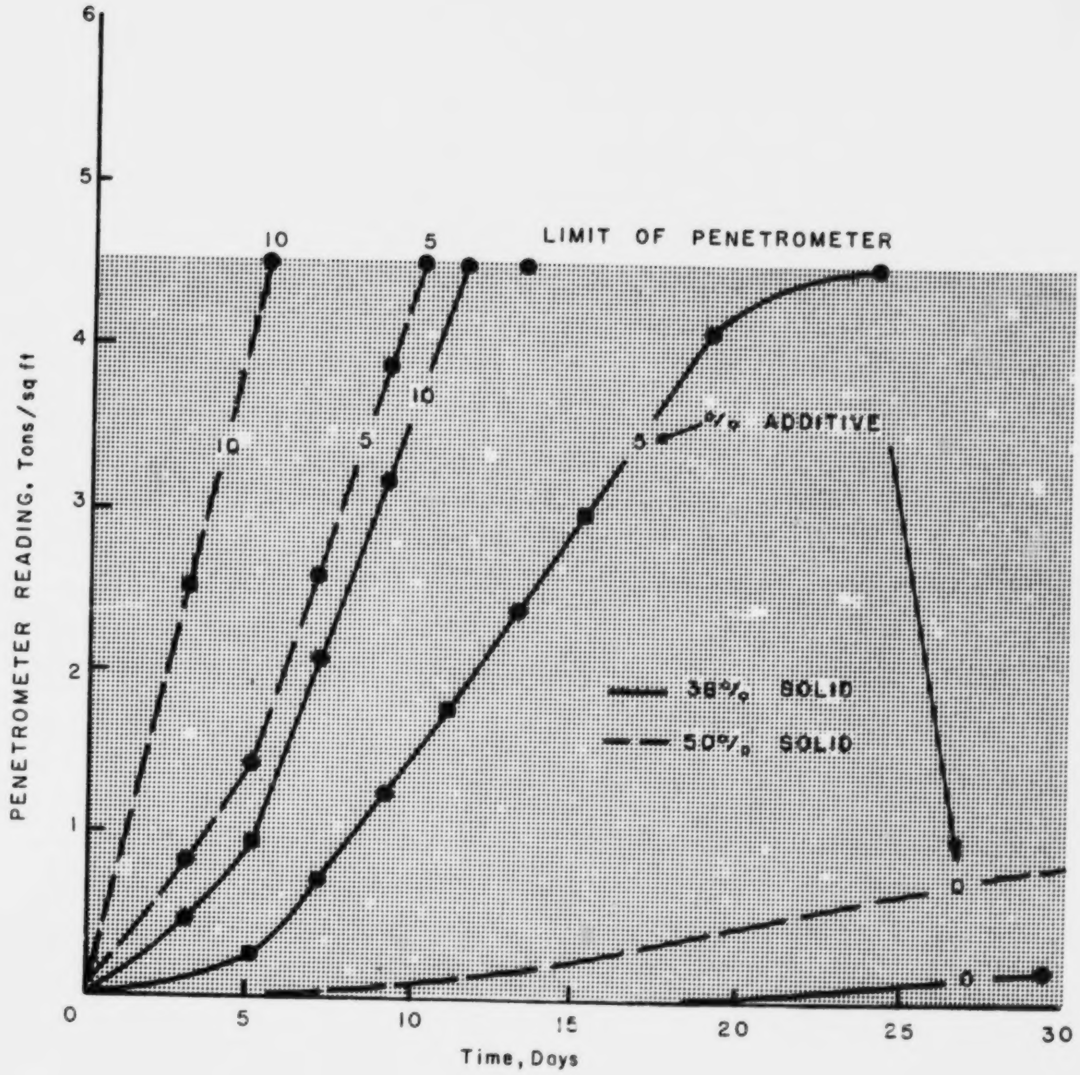


Figure II-9. Effect of Solid Content and Percent Dravo Additive on the Strength (Ref. 47).

Untreated sludges reportedly have very poor dimensional stability. On exposure to drying conditions, shrinkage and cracking were observed (Ref. 38). Linear shrinkage of 3.7 percent was measured for Shawnee sludge. This was found to be a function of water content. This phenomenon can be prevented by addition of a pozzolanic material such as is involved in most of the stabilization processes now offered. IUCS has reported the results of behavior of Sulf-O-Poz® material molded into 2.5 x 2.5 x 25 cm bars and cured at 23°C (Ref. 9). In each case, an initial slight expansion was observed; the degree of expansion leveled off within 3-4 weeks for low lime content samples and within 5-6 weeks for high lime samples, with respective overall increases in length of ∿0.003 and 0.008 cm/cm. Field tests to date have produced good results with regard to structural integrity.

3.3 Support of Vegetation

An additional factor to be considered in reclamation of abandoned scrubber sludge disposal sites is whether growth of vegetation can be supported on the area. At the present time, no studies are available directly concerning this aspect. However, Chemfix has reportedly grown grass on fixed industrial waste sludges to which only fertilizer was added (Ref. 48).

E. OTHER DISPOSAL METHODS

Another possible option available for disposal of ash and sludge, although not under investigation to the same extent as landfill and ponding, involves direct deposit of the waste below the surface in subsurface mines. Deep mine filling has been used for the disposal of power plant ash as a mine subsidence prevention technique (Ref. 61). The ash is sluiced into the mine through boreholes. Normally, gravity is sufficient to create a flow into the mine. Pumps and additional boreholes were provided in case of hole plugging or increased friction losses. A dewatering sump and a settling basin were formed by constructing dams across the mine floor. Overflow from the settling basin flows to the sump from which it is pumped to an above ground basin. Further details are available in the literature (Refs. 61, 62).

The feasibility of this type of approach is currently being investigated by the Bureau of Mines for disposal of lime/limestone scrubber sludges. The results from this study are not yet available. Investigation of this approach may be worthwhile to those utilities to which abandoned deep mines are available as potential disposal sites.

Another alternative which has been proposed is deep-well injection. The EPA policy is to review this alternative on a case by case basis but considers deep-well injection as a last resort only. There is no information available related to its potential use as a scrubber sludge disposal technique. The high solids content of the sludge probably would cause rapid plugging of the subsurface strata, resulting in decreased permeability and continually diminishing injection rates. There may be some very permeable formations where this would not occur.

F. CURRENT EPA R&D PROGRAMS

1.0 NERC-RTP Programs

Because of the rapid emergence of lime/limestone wet scrubbing as the near-term dominant desulfurization process, the low percentage of sludge utilization expected (see Section II-A), and a lack of knowledge regarding potential heavy metal and toxic element involvement in scrubber chemistry, NERC-RTP recently initiated activities toward ecologically sound and "safe" treatment/disposal of the waste products from non-regenerable SO_2 control processes.

A contract entitled "Wet Collected Limestone-Modified Fly Ash Characterization and Evaluation of Potentially Toxic Hazards" was formalized late in 1972 with the Aerospace Corporation. The contract provided for a detailed characterization of wet collected limestone-modified fly ash and an evaluation of the potential toxic hazards posed in processes that may be performed in subsequent handling, disposal, or utilization of the sludge. However, when procurement for the contract was initiated, potential utility sources to obtain representative sample types were limited; disposal was essentially limited to ponding; and commercial acceptability of throwaway processes and the corresponding quantity of material requiring disposal were unknown. These factors led to a program of limited scope with prime ecological emphasis on toxicity. Since that time, additional utility sources using different sorbent/fuel combinations and applying other treatment/disposal techniques have become operative. These additional combinations with their different elemental compositions and treatment/disposal techniques needed to be taken into consideration. Although toxicity was still considered important, toxic element concentrations were expected to represent only a very small percentage of the total quantities of disposal material. Additionally, the alternate disposal technique of chemical treatment (fixation) of sludge had become of greater interest. For these reasons and the current and projected magnitude of the sludge problem, NERC-RTP initiated an expanded program with Aerospace to allow a more complete assessment of ecological acceptability, technical state-of-the-art, and economics for the various treatment/disposal techniques. This new expanded program is entitled "Study of Disposal of By-products from Nonregenerable Flue Gas Desulfurization Systems."

The objectives of the expanded program, which is currently underway, are to determine ecologically and economically acceptable methods for treatment/disposal of lime/limestone sludge. Sample materials, representative of as many situations of lime/limestone wet scrubbing process applications as practicable, are being obtained. In addition, test, operational and economic data from a wide variety of sources are being taken into consideration.

The basic elements of the program are as follows:

1. An inventory of sludge components, including chemical analysis of various types of sludge and the raw materials from which they are formed (lime or limestone, coal or oil, process water). Sorbent/fuel combinations being studied are limestone/Eastern and Western coals, lime/Eastern coal, and double alkali/Eastern coal.

2. An evaluation of the potential water pollution and solid waste problems associated with disposal of the sludge, including consideration of existing, anticipated or proposed water effluent, water quality and solid waste standards or guidelines. The information will assist in the evaluation of potential treatment/disposal techniques described below.

3. An evaluation of treatment/disposal techniques with emphasis on ponding and "fixed" and "unfixed" landfill (and related land use applications). Physical analyses and tests of various sludges are being conducted, including determination of the effects of dewatering, oxidation, chemical fixation, and aging on stability, compactibility, leachability of solubles, potential pond seepage, potential run-off problems, and other disposal considerations. The economics of various treatment/disposal combinations are also being studied.

4. A recommendation of the best available technology for sludge treatment/disposal based on the evaluation described above.

The current Aerospace contract is limited to the sampling and analysis of sludges from only four power plant flue gas desulfurization (FGD) systems. Because of the diversity of coal types and FGD systems, this was felt to be too small a data base upon which to draw the general conclusions needed to achieve the program objectives. In addition, results of the current program identified the need for (1) a more detailed examination of possible scrubber system alternatives for reducing the availability of soluble chemical species to the environment, (2) greater emphasis on the cost of sludge transport for disposal, and (3) a field study of disposal of both treated and untreated FGD system sludges. Therefore, a contract modification is currently being negotiated, the purpose of which is to accomplish the following:

1. Expand the sampling and analysis effort from four plants to eight, which will make the program results applicable to a broader range of power plant flue gas scrubbing applications.

2. Determine, through analytical and laboratory solubility studies, those chemical constituents which can be controlled by scrubber chemistry. Examine the possible effect of the results of the solubility studies on cost and technical adequacy of alternative sludge disposal methods.

3. Expand disposal cost analyses to include more detailed investigations of various transport modes; e.g., trucking, pumping, and barging.

4. Support an EPA field study of FGD sludge disposal at TVA's Shawnee Steam Plant, which will include test planning, program coordination, analyses of liquid and solid samples, and reports.

In the EPA field study, sludges will be obtained from 10 Mw lime/limestone pilot scrubbers at the TVA Shawnee Power Station at Paducah, Kentucky, and will be placed into five ponds nearby. Two ponds will each receive raw lime and limestone sludge, respectively; one pond will receive chemically conditioned lime sludge; and two ponds will receive chemically conditioned (by two different processes) limestone sludge. Each pond will have a leachate well and a groundwater well. Tests shall be performed to determine the following: (1) the nature of the bottom soil of each pond; (2) the quality of the water from all wells; (3) the seepage through the bottom of all ponds; (4) the interaction between the sludges and the bottom soil of each pond; and (5) the quality of the chemically conditioned sludges as to strength, permeability, and leaching effects.

2.0 NERC-Corvallis Programs

NERC-Corvallis has initiated a contract with Aerospace Corporation directed toward determining the implications of open-loop or partially open-loop operation of lime/limestone FGD systems. Analyses of various sludge liquors will be performed and technologies for liquor treatment will be evaluated. These data will be used to ascertain the water pollution and reuse potential, for various plant uses, of treated and untreated scrubber liquors.

3.0 NERC-Cincinnati Programs

Two programs have recently been initiated at NERC-Cincinnati to evaluate the environmental effects of FGD sludge disposal. One of these is an interagency agreement with the U.S. Army Corps of Engineers' Waterways Experiment Station in Vicksburg, Mississippi. Under this agreement, the leachability and durability of raw and chemically fixed hazardous industrial wastes and FGD sludges are being studied. Five industrial sludges and up to six FGD sludges are being obtained for the study. The FGD sludges obtained so far in the study include the following:

Eastern (High Sulfur) Coal - Lime
- Limestone
- Double Alkali

Western (Low Sulfur) Coal - Limestone
- Double Alkali

The second program is also an interagency agreement, with the U. S. Army Materiel Command's Dugway Proving Ground, Dugway, Utah. Under this agreement research is being conducted to determine the extent to which heavy metals and other chemical constituents from 13 industrial and three FGD sludges could migrate through the soil in land disposal sites. After initial screening tests with a variety of U. S. soils, leachate column studies will be performed with two selected (best and worst) soils. Long-term permeability tests with selected clays are also planned for the FGD sludges.

NERC-Cincinnati is also currently considering a full-scale FGD sludge disposal demonstration program with an Eastern utility.

Additional information relevant to sludge disposal has been generated through NERC-Cincinnati efforts in mine drainage pollution control and solid waste disposal. EPA mine drainage activities have resulted in numerous reports dealing with sludge produced by neutralization of acid mine drainage. The reports cover areas such as in-situ sludge precipitation, sludge supernatant treatment, thickening and dewatering, use of latex as a soil sealant, and technical and economic feasibility of bulk transport.

Also, NERC-Cincinnati municipal sludge activities relate to the EPA sludge program under discussion. Examples include the following:

1. Methods of removing pollutants from leachate water.
2. Evaluation of landfill liners.
3. Development of mathematical models to determine effects of landfill leachate on groundwaters.
4. Leachate pollutant attenuation in soils.
5. Moisture movement in landfill cover material.
6. Forecasts of effects of air and water pollution controls on solid waste generation.

An attempt is being made to use the Aerospace program as the focal point for documenting all sulfur oxide sludge activities; close liaison is being performed by Aerospace with NERC-Corvallis, NERC-Cincinnati, sludge-producing utilities, and sludge treatment vendors.

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III. ALTERNATIVE SULFUR BY-PRODUCTS

As an alternative to recovering flue gas sulfur as a throwaway sludge, some fraction of flue gas sulfur will be recovered as potentially saleable products such as sulfur, sulfuric acid, gypsum, sodium sulfate, ammonium sulfate, and liquid SO_2. The type and quantity of sulfur by-products recovered will depend upon the status of the flue gas desulfurization production technology, various economic and marketing considerations, and various environmental considerations. A discussion of these factors along with a comparison of by-product and sludge production is the subject of this section.

A. PRODUCTION TECHNOLOGY

The status of various flue gas desulfurization processes was discussed in Section I-A of this report. A brief review, with emphasis on the product and the status of the technology required to produce it, will be given in this section.

1.0 Wellman-Lord Regenerable FGD

In the Wellman-Lord regeneration step, the absorbent (sodium sulfite, bisulfite, and sulfate) is heated in an evaporation crystallizer to yield a concentrated SO_2 gas and sodium sulfite crystals which are recycled. The high purity, high concentration SO_2 gas can be further processed to liquid SO_2, sulfuric acid, or sulfur. Sulfate formed in the scrubber by oxidation cannot be economically regenerated and is removed from the system by direct purging or selective crystallization of sodium sulfate.

Sulfuric acid production from SO_2 is a well established technology; on the other hand, the technology for SO_2 reduction to sulfur is still developing, having been commercially operated in only one plant, a smelter in Canada. For example, there has been a significant demonstration of sodium scrubbing/sulfuric acid production technology in Japan by Mitsubishi Chemical Machinery (Davy Powergas) at the Japan Synthetic Rubber's Chiba Plant. This unit has operated at almost 100 percent availability during the past 2 years, removing better than 90 percent of the SO_2 in the flue gas stream from an oil-fired boiler and producing high purity sulfuric acid. In this country EPA is currently participating in the funding of a Wellman-Lord process installation on the 115 Mw Northern Indiana Public Service Company's Mitchell Station. A 1-year demonstration is planned, starting up in late 1975. This will be the first application of the Wellman-Lord process to coal-fired boilers. The plant will also demonstrate the technology for reduction of SO_2 to elemental sulfur, a step to be carried out by the Allied Chemical process.

The sodium sulfate by-product of sodium scrubbing systems can be recovered or reacted with lime to produce gypsum and sodium hydroxide. Both operations have been successfully demonstrated by sodium scrubbing and sodium-based double alkali plants in Japan.

2.0 Magnesia-Based Processes

Like the sodium scrubbing processes, the magnesia scrubbing processes can produce liquid SO_2 , sulfuric acid, or sulfur. In the regeneration step, a sidestream of recycled slurry (magnesium oxide, sulfite, and sulfate) is sent to a crystallizer and centrifuge where hydrated crystals of magnesium sulfite and magnesium sulfate and unreacted magnesium oxide are separated from the mother liquor. Mother liquor is recycled to the scrubber and the centrifuged wet cake is dried in a rotary kiln. Dried anhydrous crystals are sent to a central plant where they are calcined to recover magnesium oxide and SO_2.

EPA has co-funded a full scale Chemico-Basic Chemicals magnesia scrubbing process installation which was started up in April 1972 on a 155 Mw oil-fired unit at Boston Edison's Mystic Station. For about 1 year, various equipment problems were experienced. However, during the last several months of this recently completed program, the system demonstrated a greater than 90 percent availability to the boiler. Regeneration of magnesium oxide and production of sulfuric acid was carried out at Essex Chemical Company. A similar system treating 100 Mw (equivalent) sidestream of flue gas from a coal-fired boiler has been installed at Potomac Electric and Power's Dickerson No. 3 Unit. The plant is in initial start-up operation.

Sulfur may be recovered from the concentrated sulfur dioxide stream by reduction with methane, carbon, or carbon monoxide. In addition, it may be possible to directly or indirectly produce elemental sulfur in the calciner by modification of the operation (Ref. 1). None of these processes has been applied in conjunction with magnesia scrubbing processes to date.

3.0 Ammonia-Based Processes

Ammonia scrubbing systems can be operated to yield ammonium sulfite, bisulfite, and sulfate, which may be recovered or regenerated yielding an essentially pure stream of sulfur dioxide that can be converted either to acid or elemental sulfur as the situation dictates. EPA is sponsoring a pilot scale evaluation of ammonia scrubbing and regeneration at the TVA Colbert steam plant. A present trend in ammonia scrubbing systems is toward an ammonia-based double alkali system where the ammonium sulfite/sulfate solution is reacted with lime or limestone to produce a throwaway sludge similar to that produced by a lime/limestone scrubbing system. As an alternative to sludge production, the ammonium sulfite can be oxidized to sulfate prior to reaction with lime or limestone to produce gypsum as a by-product. The production of gypsum from an ammonia scrubbing system has been demonstrated in Japan by the Japan Iron and Steel Federation. In this country, TVA is just beginning a demonstration of an ammonia-based double alkali system at their pilot unit at the Colbert steam plant.

4.0 Catalytic Oxidation Processes

The catalytic oxidation (Cat-Ox) process is restricted to sulfuric acid as the product. The Cat-Ox (Monsanto) system is similar to the contact acid process. The flue gas is sent to a fixed-bed converter where the SO_2 is oxidized to SO_3 in the presence of a vanadium pentoxide catalyst. Sulfuric acid is formed by contacting the SO_3-rich gas with water in an absorption tower. The product acid (75 to 85 percent sulfuric acid) is cooled and sent to storage.

EPA, Monsanto, and Illinois Power Company have been involved in the demonstration of the Cat-Ox process on a 100 Mw boiler at Wood River, Illinois. The plant was originally started in September 1972. Due to the lack of natural gas fuel, the reheaters were modified to allow the use of either gas or oil. Performance criteria were met in July of 1973. The system has experienced operating problems including plugging of the catalyst bed with fly ash, catalyst attrition during cleaning, and fly ash buildup in the final mist eliminator.

5.0 Lime/Limestone Processes

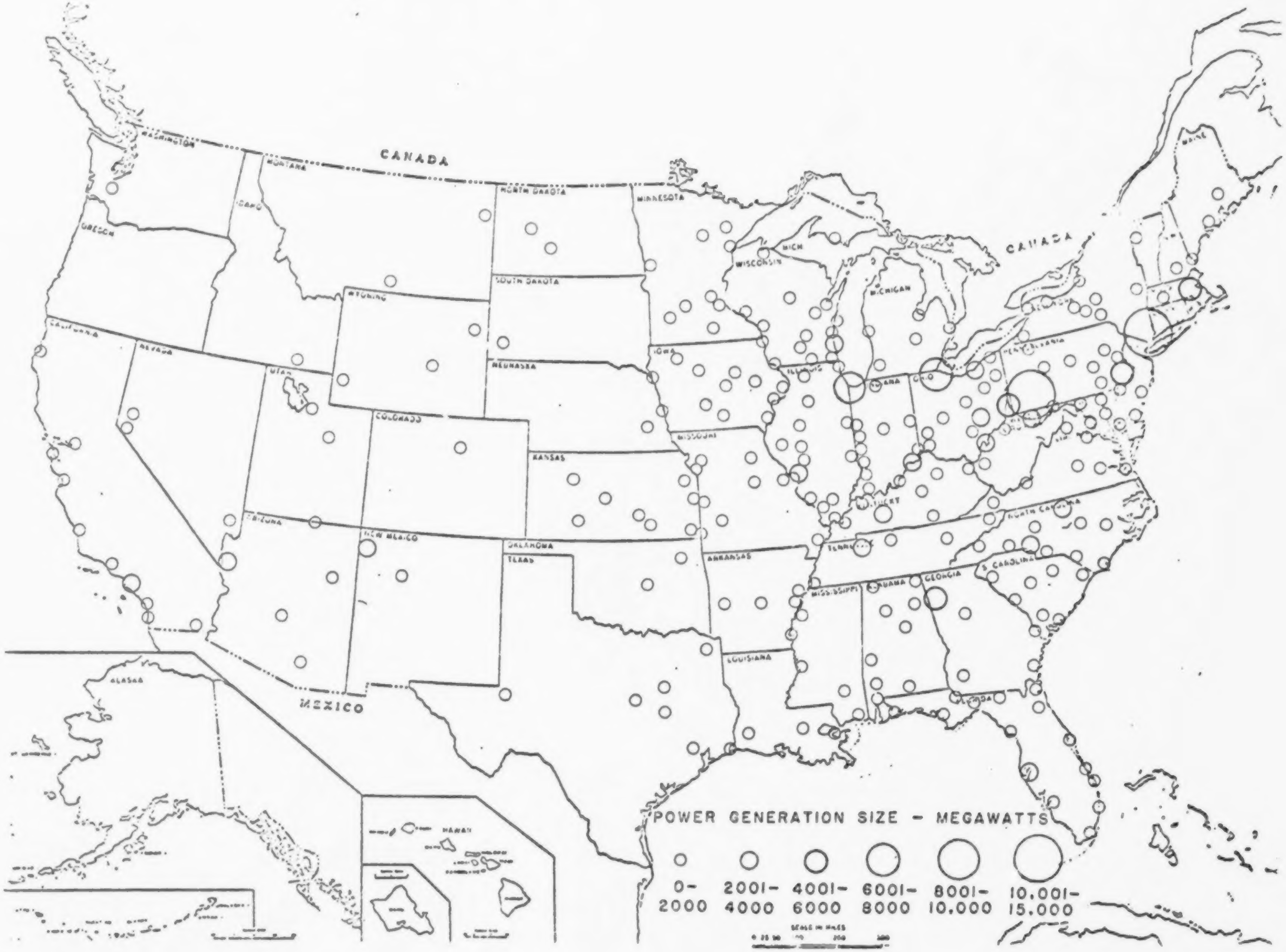
Lime/limestone processes can be operated to produce gypsum as a product instead of producing a throwaway sludge. Production of high purity gypsum requires that particulates be efficiently removed upstream of the sulfur dioxide absorber. The waste slurry stream containing calcium sulfite, calcium sulfate, and calcium carbonate or calcium hydroxide is first oxidized and then treated with sulfuric acid to convert the excess calcium carbonate or calcium hydroxide to gypsum. The resulting slurry is then centrifuged to produce high-grade gypsum containing 10-15 percent moisture.

This process has been demonstrated at a number of plants in Japan and both high-grade gypsum for use in wallboard production and lower grade gypsum (containing fly ash) for Portland cement production have been made. In this country TVA has tried to oxidize a limestone scrubbing slurry to improve settling characteristics but to date no attempt has been made to produce a marketable product.

B. ECONOMIC AND MARKETING CONSIDERATIONS

The economic and marketing factors which must be assessed to determine the market for sulfur by-products include the present and future uses for the products, the current and projected supply and demand, the geographical location of the potential markets, and the quantities which can potentially be produced by flue gas desulfurization. In this section the influence of each of these factors on the potential by-product markets for sulfur, sulfuric acid, gypsum, sodium sulfate, ammonium sulfate, and liquid SO_2 is discussed as it applies to the individual by-products.

Figure III-1, which shows the location of the major oil- and coal-fired generating stations, is included as an aid in understanding the geographical significance of the markets for various products (Ref. 1).


CANADA
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NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
MICH
MICHIGAN
ILLINOIS
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
S. CAROLINA
NORTH CAROLINA
PENNSYLVANIA
MAINE
ALASKA
HAWAII
POWER GENERATION SIZE - MEGAWATTS
0- 2000
2001- 4000
4001- 6000
6001- 8000
8001- 10,000
10,001- 15,000

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Figure III-1. Location of Major Coal- and Oil-Fired Power Plants

1.0 Sulfur

Sulfur is used for a variety of applications; sulfuric acid represents 85 percent of the elemental sulfur utilization in the U.S. (Ref. 2). Table III-1 illustrates the uses of sulfur in all forms for 1968 (Ref. 3).

The uses of sulfur in the form of elemental sulfur include the manufacture of chemicals and the manufacture of refined grades of sulfur used in agriculture and in the rubber industry.

From 1967 to 1972, the total U. S. production of sulfur in all forms fluctuated from 9.5 to 10.2 million metric tons (10.6 to 11.4 short tons) per year (Ref. 4). The high of 10.2 million metric tons per year was reached in 1972. Total production includes elemental sulfur recovered as by-product from petroleum refining and natural gas operations, by-product sulfuric acid from smelting operations, pyrites, and hydrogen sulfide and liquid sulfur dioxide recovery. As a comparison, it should be noted that the sulfur production rate from one 1000 Mw flue gas cleaning installation, operating at 70 percent load, burning 3 percent S coal with 85 percent SO_2 collection, is approximately 65,000 metric tons (72.800 short tons) per year. This represents approximately 0.65 percent of the total annual U. S. consumption of sulfur.

In the past most of the sulfur produced in the United States has been obtained from Frasch sulfur mines. In 1972, 75 percent of the domestic production of sulfur was Frasch sulfur. In this country, all of the Frasch sulfur is produced in Texas and Louisiana.

Table III-1. CONTINGENCY FORECASTS OF DEMAND FOR SULFUR (ALL FORMS) BY END USE, YEAR 2000[a]

End Use	Quantity, 10^3 Long Tons Demand 1968	U. S. Forecast Base 2000
Fertilizers	4,550	16,800
Inorganic pigments	500	...
Cellulose fibers (rayon)	570	2,000
Nonferrous metals (ore leaching)	300	1,050
Explosives	250	875
Iron and steel pickling	200	...
Petroleum refining	180	255
Alcohols	135	470
Pulp and paper	540	1,900
Other uses	1,860	6,500
Total	9,085	...

[a] Ref. 3

Between 1962 and 1972 the recovery of elemental sulfur from natural gas and crude oil desulfurization in the United States increased from 0.9 to 1.9 million metric tons (1 to 2.1 short tons) per year. This trend is expected to continue (Ref. 5) with increased recovery of sulfur at refineries anticipated due to ever-increasing imports of high sulfur crude oil and increased demand for low sulfur fuels caused by environmental regulations.

Any new supplies of by-product sulfur or other compounds from flue gas desulfurization in the utility industry would probably not be expected to displace recovered sulfur or by-product sulfuric acid from other industries. Any market penetration by the electric utilities would probably be at the expense of the Frasch producers (Ref. 6).

The minimum sulfur price required to keep a Frasch mine in operation is very difficult to estimate. Each mine is a unique situation. Operating costs vary considerably. Manderson (Ref. 5) has estimated the manufacturing costs at $7 per long ton for a low-cost producer, $11 for a medium-cost, and $15 for a high-cost producer. Rising fuel costs will certainly inflate these estimates. If a 15 percent pre-tax return on fixed investment is added, these estimates become $10, 15, and 23 per long ton. Sales, general, and administrative expenses increase these to minimum f.o.b. prices of $14, 19, and 27 per long ton. The current posted price for crude, bright molten sulfur, ex-terminal Tampa, Florida, is $28 per long ton (Ref. 7). Large users probably have contracts for considerably lower prices.

Assuming that Frasch mines would not be closed until revenues failed to cover cash expenses, and assuming that Manderson's estimates of manufacturing cost approximate cash expenses of producing Frasch sulfur, upper Midwestern utilities would have to offer sulfur at $11 per long ton delivered in Louisiana. Shipping costs to Louisiana by barge on the Tennessee, Ohio, and Mississippi Rivers are estimated to be about $6-7 per ton. Using Manderson's estimate of $4 per long ton for sales and administrative expense, it appears that upper Midwestern sulfur might be sold on the Gulf Coast if essentially no net back (no net profit) were required to justify the project (Ref. 6). Utilities located nearer to the Gulf or close to sulfuric acid plants could conceivably realize a positive net back on sulfur sales.

As was mentioned earlier, 85 percent of all sulfur consumed in the United States is used in the form of sulfuric acid. Sulfur has several advantages over acid as a product for marketing, including lower cost of storage, higher concentration for shipping, better marketing flexibility, and broader spectrum of use. It seems likely, however, that costs of by-producing sulfur from flue gas desulfurization systems will be higher than the costs of producing sulfuric acid because of the need for a reducing agent. Moreover, the basic economics are questionable since the sulfur is in the oxidized form in the stack gas and this is the form (as sulfuric acid) in which most of it is used. It is not very cost-effective to oxidize the sulfur compounds in the fuel during combustion, reduce the resulting sulfur dioxide back to sulfur, and then oxidize it again to acid before use--unless, of course, storage and shipping costs are overriding considerations (Ref. 8).

In summary, the market for sulfur as a recovery product from flue gas desulfurization systems is uncertain at this time. There is a potential market for sulfur in the sulfuric acid industry but whether it is more economical to recover the SO_2 as sulfur or sulfuric acid will depend on the process economics as they finally develop and the local considerations which will cause one product to be favored over another. In addition, the technology for reduction is not well developed and requires reducing agents (e.g., natural gas) which are scarce in some locations.

2.0 Sulfuric Acid

Sulfuric acid is the most widely manufactured chemical in the world. The major end uses for sulfuric acid are summarized in Table III-2. As can be seen from the table, over half the sulfuric acid produced in the United States is used to make phosphate fertilizers. The remaining acid is used for a wide variety of applications ranging from the production of alcohols to non-ferrous metallurgy.

According to U. S. Department of Commerce data (Ref. 10), the total production of sulfuric acid in the United States was 28,200,000 metric tons in 1972. This total represents an increase of 5.5 percent over 1971 production. Production has been increasing about 5 percent per year since 1960.

Current manufacturing capacity for sulfuric acid is nearly 36 million metric tons per year with more than half of the capacity committed to captive use. As shown in Figure III-2, states with the largest capacity for acid manufacture include Florida, Louisiana, Texas, New Jersey, and Illinois (Ref. 1). A state-by-state breakdown of capacity is shown in Table III-3.

The U.S. production of by-product smelter acid in 1972 was reported as equivalent to 0.55 million metric tons (0.60 short tons) of sulfur. Much of the by-product sulfuric acid is produced in the Western states, but there are three smelters in

Table III-2. SULFURIC ACID END USE PATTERN 1970[a]

	Thousand Short Tons (100% Basis)
Fertilizer	
Phosphoric acid products	13,750
Normal superphosphate	1,240
Cellulosics	
Rayon	520
Cellophane	170
Pulp and paper	600
Petroleum alkylation	2,400
Iron and steel pickling	800
Nonferrous metallurgy	
Uranium ore processing	300
Copper leaching	350
Chemicals	
Ammonium sulfate - coke oven	500
synthetic	480
chemical byproduct	190
Chlorine drying	150
Alum	600
Caprolactam	260
Dyes and intermediates	370
Detergents, synthetic	400
Chrome chemicals	100
HCl	150
HF	880
TiO$_2$	1,440
Alcohols	1,800
Other chemicals	380
Industrial water treatment	200
Storage batteries	140
Other processing	470
TOTAL	28,640

[a] Ref. 9

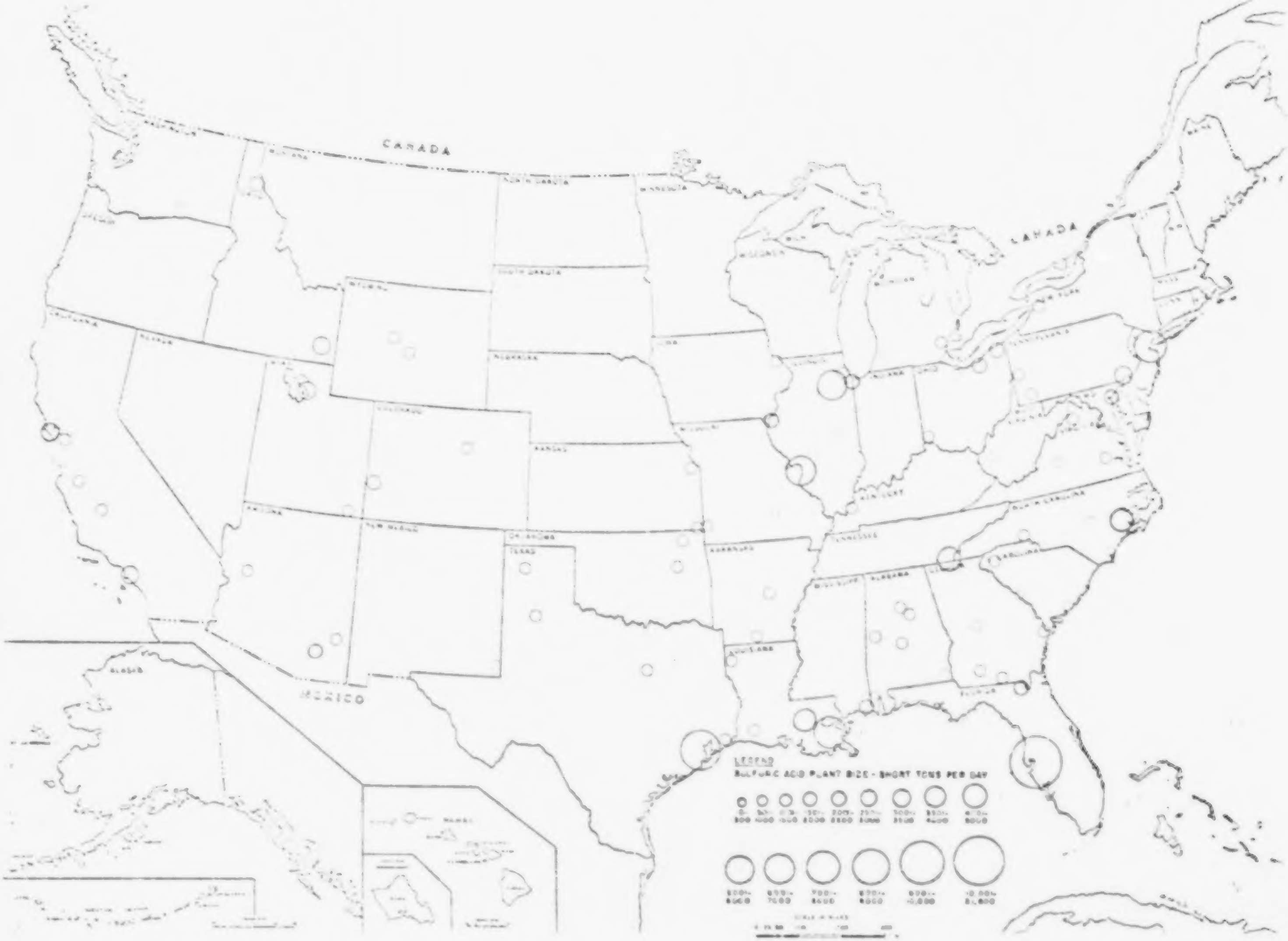
CANADA
CANADA
MEXICO
LEGEND
SULFURIC ACID PLANT SIZE - SHORT TONS PER DAY

Figure III-2. Sulfuric Acid Manufacturing Capacity (Ref. 1).

Table III-3. SULFURIC ACID PLANT CAPACITY[a]

State	Capacity, short tons per day	State	Capacity, short tons per day
Alabama	1,610	Mississippi	1,067
Arizona	2,627	Missouri	3,303
Arkansas	737	New Jersey	6,913
California	6,774	New Mexico	446
Colorado	1,483	New York	583
Delaware	1,050	North Carolina	3,480
Florida	23,661	Ohio	3,180
Georgia	1,369	Oklahoma	630
Idaho	3,470	Pennsylvania	2,177
Illinois	6,944	Rhode Island	50
Indiana	2,066	South Carolina	324
Iowa	1,877	Tennessee	4,421
Kansas	747	Texas	9,855
Kentucky	550	Utah	2,133
Louisiana	12,600	Virginia	1,983
Maine	223	Washington	333
Maryland	2,260	West Virginia	470
Massachusetts	330	Wisconsin	67
Michigan	1,301	Wyoming	360
		Grand total	113,454

[a] Ref. 11

the Eastern United States (one each in Ohio, Western Pennsylvania, and Tennessee) that affect Eastern markets. In addition, another smelter is scheduled to start up in Kentucky in 1976.

A 1000 Mw generating station operating at 70 percent load, burning 3 percent sulfur coal, and equipped with a flue gas desulfurization system recovering 85 percent of the SO_2 from the flue gas, could produce approximately 200,000 metric tons (220,000 short tons) of sulfuric acid per year. This is equivalent to slightly less than 1 percent of the present capacity for sulfuric acid production in the United States.

In the Southwest and Mountain areas the long distance to adequate markets, the limited acid consumption in these areas, and the large sulfur dioxide emissions from smelters combine to make by-product acid production for sale a very dubious proposition. In a study made for EPA by the Arthur G. McKee and Company (Ref. 12), it was estimated that only about 60-65 percent of the sulfur dioxide emitted from Western smelters could be sold as acid [4.5-5.0 million metric tons (4.95-5.5 short tons) per year], and that this could be done only if the acid were priced at $4 per ton. This leaves the remainder of smelter acid capacity and all of that from potential flue gas desulfurization plants in this area as essentially unsaleable.

Probably the best situation for by-product acid production is that in which a process for using the acid is operated contiguous to the power plant, thus avoiding the cost of shipping and marketing the acid. A phosphate fertilizer plant is the most likely prospect because a great deal of the sulfuric acid consumption is in the fertilizer industry. Phosphoric acid, triple superphosphate, and ammonium phosphate are the logical end-products.

An appropriate location for such a joinder of processes is the Upper Midwest, where over half of the phosphate fertilizer produced in the United States is consumed and where many of the power plants burning high-sulfur coal are located. It should be noted, however, that there are many drawbacks to such an arrangement, the main one being that the sulfuric acid must be used as it is produced (unless expensive surge storage is installed). Thus, the fertilizer facility would have to be operated even at times when otherwise it would not be economical to do so (Ref. 8). Alternatives to continuing fertilizer production during the period of reduced fertilizer demand would include: (1) neutralizing the acid, (2) marketing the acid for other uses (if possible), and (3) acid storage. Obviously, the relative attractiveness of these alternatives will depend on the length of time of reduced demand, local fertilizer and acid marketing conditions, plant conditions for neutralization, storage costs, and others.

A study conducted by TVA for EPA has indicated that much of the acid producing capacity in an 11-state area from the Upper Midwest to the Gulf Coast is old and will soon require replacement, expansion, or the addition of sulfur abatement equipment which will increase the producer's cost of acid. In many cases these manufacturers may be willing to buy sulfuric acid from utilities rather than invest in modifications to existing equipment (Ref. 13).

In summary, it appears that there may be an opportunity for by-product sulfuric acid from flue gas desulfurization systems to displace some of the production from elemental sulfur, at least in the 11-state area considered by TVA in this study (Alabama, Arkansas, Florida, Illinois, Indiana, Kentucky, Louisiana, Tennessee, Missouri, Ohio, and Texas). The high cost of storage and shipping, and the vagrancies of the market are major problems. The overall problem of marketing sulfuric acid is quite complicated, too much so for any full treatment in this report. The TVA market study for by-product acid funded by EPA should be useful in evaluating the situation; the TVA power system was used as an example. An analysis made of potential quantity of acid, shipping cost to various points, and the amount of acid that could be produced and marketed was calculated for various levels of networks (Ref. 8).

The base-case market study showed that the most likely maximum price allowing sale of all the abatement acid produced by TVA was $8.76 per short ton plus freight. At $10 per ton, only about half the acid could be sold; $20 per ton would be a prohibitive price resulting in no sales. Adjustments to the model gave a "most likely" maximum price as $5.99 per ton (Ref. 9).

3.0 Gypsum

There are three major commercial applications of gypsum in the United States. Over 70 percent of the total gypsum used is consumed in the manufacture of gypsum wallboard and plaster, 18 to 22 percent is used as a Portland cement retarder, and 7 to 8 percent is used as a source of sulfur in sulfur deficient soils.

Table III-4 shows the U. S. gypsum production statistics from 1962 to 1972. This table shows that there has been little growth in gypsum products during the past 10 years. Production has remained between 13.6 and 15.4 million metric tons (15 to 17 million tons) per year. Production increased to 18.2 million metric tons (20 million tons) in 1972 due to a rapid increase in construction activity which many economists expected to decline in 1973 or 1974.

TABLE III-4. U. S. GYPSUM STATISTICS (Thousands Short Tons)[a]

	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Crude gypsum mined	9,969	10,388	10,684	10,033	9,647	9,393	10,018	9,905	9,436	10,418	12,367
Crude gypsum imported for consumption	5,421	5,490	6,258	5,911	5,479	4,569	5,474	5,858	6,128	6,094	7,718
Total crude gypsum, mined & imported	15,390	15,878	16,942	15,944	15,126	13,962	15,492	15,763	15,564	16,512	20,085
Gypsum calcined	8,819	9,181	9,440	9,320	8,434	7,879	8,844	9,324	8,449	9,526	11,984

[a] Refs. 14, 15

There is virtually no merchant market in gypsum. Gypsum is mined, calcined, and sold by integrated companies. Even imported gypsum is usually from captive mines. In order to interest the major gypsum companies in by-product gypsum, it would probably have to be priced at $2 to $2.50 per ton in those parts of the country where there are large seams of high-quality gypsum. Where the quality of mined gypsum is low and some beneficiation is required before processing, it may be possible to obtain as much as $3 per ton delivered to a calcining plant (Ref. 6). A preliminary study by TVA suggests that by-product gypsum might be sold for $2.00 per ton, $0.38 per ton less than imported and $1.93 per ton less than domestic gypsum. The study further suggests that by-product gypsum can be shipped via inland waterways to local facilities for $0.65 to $7.45 per ton cheaper than imported gypsum (Ref. 9). Thus, there may be some potential market for gypsum for wallboard manufacture. On the other hand, before by-product gypsum from flue gas desulfurization systems could be sold to a wallboard manufacturer, it would be necessary to determine if the gypsum were of wallboard quality. By-product gypsum from a coal-fired plant, for example, might contain impurities that would affect wallboard manufacture.

The Japanese Chiyoda "Thoroughbred 101" process which produces wallboard quality gypsum is undergoing testing at a Gulf Power Company plant in Florida (Ref. 9). Start-up was planned for March of 1975.

Another factor affecting the use of by-product gypsum concerns the use of gypsum as a source of sulfur in sulfur-deficient soils. However, almost the entire amount of gypsum (1 million metric tons per year out of a total of 1.2 million metric tons per year) used for this purpose is consumed in California, far from the major coal-fired generating centers in the East. Thus, there is little potential for gypsum marketing for this purpose.

Further accentuating the poor by-product market for gypsum is the fact that a 1000 Mw generating plant operating at 70 percent load, burning 3 percent sulfur coal, and equipped with a flue gas desulfurization system removing 85 percent of the SO_2 from the flue gas, could produce approximately 0.4 million metric tons of gypsum per year. This is 3 percent of the total gypsum production in the United States. Thus, although there is some potential market for by-product gypsum in this country, the probable upper limit of the potential market is small compared to the potential by-product production rate.

4.0 Sodium Sulfate

The two major uses of sodium sulfate are the production of pulp in the Kraft pulp industry and the production of glass. The Kraft pulp industry consumes 67 percent of all production. The glass industry runs a distant second, consuming 12 percent. Other users of sodium sulfate are the detergent industry, the dyeing industry, the sponge industry, and other miscellaneous industries.

Table III-5 shows the production and consumption statistics for the sodium sulfate industry (Ref. 16). This table illustrates the lack of any growth trend in sodium sulfate production during the 8 years from 1964 to 1971. The demand is presently about 1,450,000 metric tons (1.6 million tons) per year of which about 182,000 metric tons (200,000 tons) per year is important.

The supply of sodium sulfate in the United States falls into two categories, natural and by-product. Natural sodium sulfate from California and Utah accounts for 40 percent of both production and capacity, although no more than 20 percent

Table III-5. PRODUCTION STATISTICS FOR THE SODIUM SULFATE INDUSTRY

	1964	1968	1971
Consumption including imports, million tons[a]	1.56	1.73	1.59
Domestic production, million tons[a]	1.32	1.48	1.35
Capacity, million tons[a]	1.72	1.68	1.52
Operating level, % of capacity	77.00	88.00	89.00

(a) Units are short tons

of the market is located west of the Rocky Mountains. The natural product from Texas accounts for 10 percent of production capacity; by-product sources, primarily east of the Mississippi River, account for about 50 percent. Thus, about half of the Far West production must cross the Rockies and absorb a freight penalty of perhaps $10-$15 per ton.

By-product sodium sulfate is derived from production of rayon, cellophane, hydrochloric acid, dichromate, phenol, basic acid, etc. Production capacity of by-product sodium sulfate east of the Rocky Mountains is approximately 818,000 metric tons (900,000 tons) per year. The Eastern market is approximately 1,180,000 metric tons (1,300,000 tons), of which 182,000 metric tons (200,000 tons) is supplied by imports and 182,000 metric tons (200,000 tons) is supplied by Western production. Recent environmental regulations affecting the rayon industry could cause the by-product production by this industry to double, making the section of the country east of the Rockies self-sufficient with respect to sodium sulfate production (Ref. 16).

The supply of by-product sodium sulfate to Eastern markets will be more than ample in the foreseeable future and that will make it difficult for potential by-product sodium sulfate from flue gas desulfurization systems to enter the Eastern markets.

A 1000 Mw generating plant operating at 70 percent load, burning 3 percent sulfur coal, and with a flue gas desulfurization system recovering 85 percent of the SO_2, could produce 300,000 metric tons (330,000 tons) per year of sodium sulfate. This is equivalent to the present consumption west of the Rocky Mountains. Even sodium-based flue gas desulfurization systems producing sulfuric acid as the primary by-product would produce

15,000 and 30,000 metric tons per year sodium sulfate (based on 5 to 10 percent of the sulfur removed being blown down as waste sodium sulfate). It is apparent that the sale of sodium sulfate as a primary by-product from flue gas desulfurization systems is not feasible on a large scale basis. Even secondary production of sodium sulfate may not find an outlet market and therefore may have to be reacted with lime or limestone for disposal or sale as gypsum. Alternatively, the sodium sulfate could be discarded at sea (which is the current practice in Japan), if this is environmentally acceptable.

5.0 Ammonium Sulfate

Essentially all of the ammonium sulfate consumed in the United States is used in fertilizers, both as a source of nitrogen and as a source of sulfur. In fiscal year 1972, the U.S. consumption of ammonium sulfate for direct application in fertilizer was about 1.9 million metric tons (Ref. 17). Table III-6 shows that, if anything, the market for ammonium sulfate has decreased during the past 5 years.

In the Eastern United States, all of the ammonium sulfate produced is by-product material. Much of this by-product ammonium sulfate is derived from coke ovens. Other sources of by-product ammonium sulfate include acrylonitrile production and caprolactam manufacture. In 1971, U. S. production of by-product ammonium sulfate from coke ovens was 0.49 million metric tons (0.54 short tons) and chemical by-product ammonium sulfate production was 1.1 million metric tons (1.21 million short tons) for a total of nearly 1.6 million metric tons (1.76 million short tons). If caprolactam manufacture continues to expand as it has in the past 3 years, total by-product ammonium sulfate may soon exceed the total production of ammonium sulfate in 1970 (Ref. 17).

Table III-6. U. S. AMMONIUM SULFATE PRODUCTION AND INVENTORY LEVELS[a]

	Quantity, 10^3 short tons material			
	1967	1968	1969	1970
Production				
Synthetic NH_4SO_4	1,074	895	774	630
Coke-oven by-product	746	716	648	595
Other by-product NH_4SO_4	837	1,097	1,157	1,259
Total production	2,657	2,708	2,579	2,484
Inventory Levels Total NH_4SO_4				
End of year	474	439	658	615
High for one month	474(Dec.)	511(Feb.)	658(Dec.)	735(Feb.)
Low for one month	223(May)	355(May)	312(July)	588(June)
Average monthly level	355	425	426	644

[a] Ref. 18

Ammonium sulfate is a poor source of nitrogen (21 percent N) compared with ammonium nitrate (33.5 percent N) and urea (46 percent N). Industry prefers to use the higher analysis fertilizers in order to minimize transportation, storage, and handling costs per unit of nutrient. The sulfur content of ammonium sulfate is important only in those areas where soils are deficient in sulfur (primarily California and parts of the Southeastern United States). For these reasons the use of ammonium sulfate fertilizers is decreasing.

It appears that with the lack of growth in demand for ammonium sulfate, the increased by-product production from coke ovens and caprolactam manufacture should more than adequately supply the U. S. consumption. For this reason by-product production from flue gas desulfurization could not expect to compete with existing by-product production for market.

Further accentuating the poor by-product market for ammonium sulfate is the fact that a 1000 Mw generating plant operating at 70 percent load, burning 3 percent sulfur coal, and equipped with a flue gas desulfurization removing 85 percent of the SO_2 from the flue gas, could produce approximately 0.3 million metric tons (0.33 short tons) of ammonium sulfate per year. This is roughly 16 percent of the present annual production.

6.0 Liquid SO_2

Sulfur dioxide is sold for use as a preservative and bleach in foods, for solvent refining of lubricating oils, for preparation and bleaching of sulfite pulp and paper stock, for conversion to sulfur trioxide, and as a disinfectant and fumigant. It is not feasible to ship sulfur dioxide in the gaseous state; therefore, the entire merchant market for sulfur dioxide is for the liquid.

Although the markets for liquid SO_2 are diverse, the demand is small. The total U. S. production in 1971 was reported to be 86,740 metric tons (95,414 short tons) (Ref. 10). From 1967 to 1971 production of liquid SO_2 fluctuated from 75,000 to 92,000 metric tons (82,500 to 101,200 short tons) per year. The total reported U. S. production capacity for liquid SO_2 is reported to be 140,000 metric tons (154,000 short tons) per year.

There would appear to be no market for liquid SO_2 as a by-product from flue gas desulfurization systems. A 1000 Mw generating station operating at 70 percent load, burning 3 percent sulfur coal, and equipped with a flue gas desulfurization system recovering 85 percent of the SO_2 from the flue gas, could produce approximately 140,000 metric tons (154,000 short tons) of liquid SO_2 per year. This is equivalent to the entire present capacity for liquid SO_2 production in the United States.

Liquid SO_2 might be an intermediate form for transportation and/or short-term storage. It retains the flexibility of being converted to acid when a market exists and to sulfur or gypsum for disposal during long periods of weak acid markets. During short periods of weak markets liquid SO_2 could be stored with approximately the same difficulty of storing ammonia for later acid production.

C. ENVIRONMENTAL CONSIDERATIONS

The various environmental factors which must be considered in the production of sulfur by-products from utility plant flue gas desulfurization systems include: the pollution potential of the by-product produced, any storage and handling problems which might ultimately affect the environment, and any ecological problems associated with disposal of the by-product in the event that the market fails or becomes inadequate. In this section each of these factors is discussed for each of the potential sulfur by-products (sulfur, sulfuric acid, gypsum, sodium sulfate, ammonium sulfate, and liquid SO_2).

1.0 Sulfur

Sulfur as a by-product from utility plant flue gas desulfurization systems would be recovered in the form of a dry, yellow crystalline solid. In this form sulfur can be stacked above ground or in closed buildings for storage. It is virtually insoluble in water although there is some possibility that wind and water erosion plus oxidation could produce acid constituents subject to leaching if the sulfur pile is not covered. Sulfur produced by reducing sulfur dioxide to hydrogen sulfide and using the Claus process to produce sulfur may contain up to about 0.01 percent hydrogen sulfide which could produce an objectionable odor (Ref. 8). This odor probably could be easily handled from a covered sulfur pile.

Even where a market is available for all of the sulfur produced by a flue gas desulfurization system, storage and handling facilities will be required to move the sulfur to market. For short-term storage an uncovered pile could probably be used with few environmental problems. For longer term storage covered sulfur piles or blocked sulfur storage probably would be adequate. The economics and environmental attributes of these storage methods need further evaluation.

2.0 Sulfuric Acid

Sulfuric acid produced as a by-product from flue gas desulfurization will vary in content from 80 to 98 percent H_2SO_4, and in quality from a high grade water-white acid to a lower grade acid containing fly ash impurities. If sulfuric acid is allowed to reach the environment, the pollution potential is obviously great. The main environmental concern would be water pollution resulting from an acid spill. Another potential pollution problem associated with the production of sulfuric acid from the recovered sulfur dioxide would be the SO_2 emission from the acid process. Normally, tail gases from the acid production portion of regenerative flue gas desulfurization systems are returned to the scrubbing system for recovery of the SO_2.

Storage and handling should not produce any additional environmental problems. It will be necessary to take proper steps to ensure that no spills occur and to be prepared to neutralize a spill in the event that one should occur.

In the event that the market for by-product sulfuric acid fails, all of the production of sulfuric acid from a flue gas desulfurization system must be either stored or neutralized and disposed of.

Work is under way to determine the best method of neutralization. The preferred method, if feasible, is to react the acid directly with limestone to make a solid gypsum product, thus avoiding the need for a solids separation step. The product slurry should set up in a short time to a solid that can be handled and piled, but several weeks will be required to attain complete reaction. Transfer of the solid to a landfill disposal area before the reaction is complete could pose an "acid leach" problem.

An alternative disposal method involves diluting the acid, reacting it with limestone, and separating the solid. Complete reaction can be obtained in the dilute system, and the solids can be washed to remove occluded acid.

If sufficient land is available for disposal of the neutralized acid and if adequate precautions are taken to eliminate "acid leach" from the landfill, the disposal of neutralized acid should not pose any serious environmental problems.

3.0 Gypsum

Gypsum as a by-product from utility plant flue gas desulfurization systems would be recovered as a fairly fine white-to-gray crystalline solid containing 10 to 15 percent moisture. Pure gypsum has essentially no pollution potential, except for its intermediate solubility. It dewaters easily and would allow land reclamation from storage ponds. However, the liquor associated with the gypsum recovered from utility plant flue gas desulfurization systems may be high in dissolved solids similar to those found in the water associated with the sludge from lime/limestone flue gas desulfurization systems. Unless the by-product gypsum were washed, these dissolved solids in the water contained by the gypsum would represent a potential run-off and leaching problem. Run-off and leaching could occur from by-product gypsum used as a direct application fertilizer or stored in piles and ponds for disposal or marketing.

Washed by-product gypsum should be identical to pure gypsum relative to environmental problems associated with storage and handling or disposal. The wash water may contain excessive levels of dissolved species, however, which may require treatment.

4.0 Sodium Sulfate

By-product sodium sulfate from power plant flue gas desulfurization systems would be recovered as a dry white crystalline solid. The high solubility of sodium sulfate would create a potential water pollution problem if exposed to water. Enclosed storage and handling facilities would have to be provided for handling soluble by-product sodium sulfate in order to prevent run-off and leaching problems.

Non-marketable sodium sulfate would have to be disposed of. The preferred method of disposing of waste sodium sulfate is to react a bleed stream of dilute sodium sulfate from the scrubber with lime to produce gypsum as a throwaway or possible saleable product. The environmental problems associated with the disposal of gypsum have been previously discussed. Alternatively, sodium sulfate can be directly discharged to the sea as is currently practiced in Japan.

5.0 Ammonium Sulfate

Ammonium sulfate as a by-product from power plant flue gas desulfurization systems would be recovered as a very fine dry crystalline solid. The high solubility of ammonium sulfate would create a potential water pollution problem and the fineness of the product would create a potential air pollution problem. Enclosed storage and handling facilities would have to be provided for handling soluble by-product ammonium sulfate in order to prevent run-off and leaching problems. Enclosed storage and handling facilities will also eliminate the potential air pollution problem caused by the dusting tendency of the very fine recovered by-product ammonium sulfate.

Disposal would be necessary for non-marketable ammonium sulfate. The preferred method of disposing of waste ammonium sulfate is to react a bleed stream of dilute ammonium sulfate from the scrubber with lime to produce gypsum. The environmental problems associated with the disposal of the gypsum have already been discussed.

6.0 Liquid SO_2

By-product sulfur dioxide from power plant flue gas desulfurization systems would be recovered as a liquified gas. This gas would be stored in tanks and shipped in tank cars. The only potential pollution would be air pollution caused by SO_2 leaking off into the atomosphere.

Disposal of unmarketable liquid SO_2 would be a complicated process probably resulting in ultimate disposal as gypsum.

Due to the extremely poor market for by-product liquid SO_2 (indicated in the previous section on economic and marketing considerations), it is assumed for the purpose of this discussion that either no by-product liquid SO_2 will be produced or small amounts will be produced captively. Based on this assumption no disposal of liquid SO_2 is anticipated.

D. ECONOMIC AND ENVIRONMENTAL COMPARISON WITH SLUDGE

In this section a comparison of all the major sulfur by-products of flue gas cleaning (sludge, sulfur, sulfuric acid, gypsum) will be discussed. Table III-7 is a comparison summary of all sulfur by-products from FGD processes. Because the other by-products have relatively small marketing potential and comparatively major disposal problems if not sold (although most can easily be converted to gypsum), they will not be discussed in the remainder of this section. The discussion relates to the relative merits of the by-products themselves and disregards the state-of-the-art of the processes which produce them. Additionally, any discussion of these alternative by-products clearly is dependent on the ultimate costs of the technologies involved, and local economic, marketing, environmental, transportation, and

Table III-7. COMPARISON OF ECONOMIC, MARKETING, AND DISPOSAL ASPECTS OF FLUE GAS CLEANING BY-PRODUCTS

By-product	Annual Production From 1000 Mw Generating **Plant with FGD**[a], metric tons/yr	Current U.S. **Consumption**, metric tons/yr	Current Market **Price**, $/metric ton	Maximum FGD System **Credit**[b], mills/Kwh	Ability to Penetrate Market	Alternatives for Non-marketable By-product	Product Disposal-Related Advantages/Disadvantages[c] As Compared to Untreated Scrubber Sludge
Sulfur	65,300	10,000,000[d]	22-31	0.22	Fair (Up to about 5% of market will probably be penetrated. Fair chance of 10-30% of market either as S or H_2SO_4 since it is essentially the same market.)	Store/dispose (piles)	(1) Much less bulk (2) Less soluble (3) Dry (4) Potentially flammable (5) Potential H_2S odor problem (6) Potential erosion problem (7) Susceptible to chemical and biological oxidation.
Sulfuric Acid	200,000	28,200,000[e]	11-16	0.34	Good (Excellent chance of penetrating 75% of market. Good chance of penetrating 10-30% of market.)	Store Neutralize & dispose as gypsum (piles, ponds, landfills)	Disposal product: gypsum (1) Less bulk (2) Easier to dewater
Gypsum	351,000	18,000,000[f]	3-4	0.16	Questionable (Not demonstrated that wallboard-grade gypsum can be made. All agricultural gypsum used in California. Portland cement gypsum must be 1/4"-2" in size. By-product would have to be pelletized.)	Store/dispose (ponds, piles, landfills)	(1) Less bulk (2) Easier to dewater
Sodium Sulfate	290,000 (Produced by Wellman-Power Gas process as a purge equal to about 5-10% of the sulfur in the incoming flue gas)	1,450,000[g]	16-27	0.72	Limited (Eastern market supplied by present by-product production. Western market equal to output from one 1000 Mw plant)	Store Neutralize & dispose as gypsum (ponds, piles, landfills)	Disposal product: gypsum (1) Less bulk (2) Easier to dewater

Table III-7 **(Continued)** COMPARISON OF ECONOMIC, MARKETING AND DISPOSAL ASPECTS OF FLUE GAS CLEANING BY-PRODUCTS

By-Product	Annual Production From 1000 Mw Generating **Plant with FGD**[a], metric tons/yr	Current U.S. **Consumption**, metric tons/yr	Current Market **Price**, \$/metric ton	Maximum FGD System **Credit**[b], mills/Kwh	Ability to Penetrate Market	Alternatives for Non-marketable By-product	Product Disposal-Related Advantages/Disadvantages[c] As Compared to Untreated Scrubber Sludge
Ammonium Sulfate	270,000	2,[illegible],000[h]	27-35	1.14	Poor (66% of market presently supplied by by-product from chemical industry. Projected to increase to 100% by 1980.)	Store Neutralize & dispose as gypsum (ponds, piles, landfills)	Disposal product: gypsum (1) Less bulk (2) Easier to dewater
Liquid SO_2	130,000	**86,740**[i]	N/A	N/A	Poor (Production from one 1000 Mw plant is greater than total U.S. market consumption)	Store Convert to S or gypsum and dispose	Disposal product: gypsum (1) Less bulk (2) Easier to dewater
Sludge	710,000 (784,000 short tons)	------	------	------	--------- Possible penetration of road bed & synthetic aggregate market.	Untreated disposal (ponds) Treated disposal (landfill)	(1) Improved physical properties (2) Less soluble (3) Reduced permeability & leachability

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[a] **6400 hr/yr operation, 3% S, 0.4 kg coal/kw-hr, 85% SO_2 removal efficiency.**

[b] Assuming 100% sale of product at lowest market price.

[c] There are potential ground and surface water pollution and land wastage/reclamation problems with all disposal products shown. Untreated **scrubber** sludge may have high potential for these problems.

[d] Ref. 4

[e] Ref. 1

[f] Ref. 15

[g] Ref. 16

[h] Ref. 17

[i] Ref. 10

land use considerations. However, a few general observations seem to be appropriate:

1. If a reliable market exists probably the most environmentally attractive sulfur by-products are sulfur and sulfuric acid; at reasonable prices for the saleable product such regenerable processes are economically competitive with lime/limestone systems. However, it should be noted that the same quantities of soluble species which originate in the coal would have to be purged from sulfur and sulfuric acid producing systems.

2. If acid cannot be marketed relatively reliably, sulfur and gypsum storage probably are the most attractive alternatives on an environmental basis. From an environmental viewpoint, the only alternative by-products which can safely be disposed of in their natural states are sulfur and gypsum. Sulfuric acid, sodium sulfate, and ammonium sulfate would require conversion to gypsum prior to disposal. Disposing of liquid SO_2 in an environmentally safe manner could probably not be done without conversion to sulfuric acid with subsequent neutralization. Sulfur affects much less land (90 percent less land) and has less water pollution potential than sludge (see Table III-8) and has the additional benefit of providing potential long-term sales. Unlike sludge and gypsum, waste sulfur may have far-term future potential if the world sulfur market becomes supply-limited near the turn of the century as some studies have indicated (Ref. 19). Utilities which had discarded sulfur could reclaim it and sell it when the price

Table III-8. COMPARISON OF THE AMOUNT OF LIMESTONE SLUDGE, SULFUR, AND GYPSUM THAT CAN BE PRODUCED BY A 1000 Mw COAL-FIRED GENERATING STATION[a]

Sulfur By-Product	Production (metric tons/yr)	Storage Requirements[b] (cubic meters)
Wet Limestone Sludge (50% moisture)	693,000	480,000
Sulfur (dry)	65,300	47,000
Gypsum (10% moisture)	390,000	210,000

[a] Assumptions: 6400 hr/yr operation, 3% S, 12% ash, 0.4 Kg coal/kwh, 85% SO_2 removal efficiency, sulfite/sulfate mole ratio of 9:1 in the sludge, $CaCO_3$/SO_2 (inlet) mole ratio of 1.2.

[b] Assuming a storage requirement of 0.72 m^3/metric ton (23 ft^3/ton) for sulfur, 0.69 m^3/metric ton (22 ft^3/ton) for sludge, and 0.72 m^3/metric ton (23 ft^3/ton) for gypsum.

and time were right. This would amount to a national stockpile of a strategic manufacturing material. Gypsum also should be preferable to sludge but not to sulfur due to volume (Table III-8) and physical and chemical properties; gypsum might also be marketed at some later date.

3. Sludge is the least attractive by-product unless it can be safely disposed of as landfill in an economical manner. If ponding is required without treatment much larger masses of much less attractive material must be stored. This causes a land utilization problem and has to be viewed as less desirable environmentally than a much smaller pile of sulfur or gypsum.

It is expected that the first alternative above, saleable acid or sulfur, will make up a maximum of 50,000 Mw equivalents by 1980. This corresponds to approximately 50 percent of today's acid market and approximately 45 percent of the expected capacity of FGD in 1980. Thus, at least 50,000 Mw equivalents of sulfur by-products must be stored or disposed of (as sludge or as sulfur/gypsum). The projection of current trends in the ratio of regenerable to non-regenerable processes has already been discussed. The relative total process costs of lime/limestone sludge vs. regenerable sulfur were also discussed earlier. At this point no one single process is clearly less expensive than another, although regenerable systems producing non-saleable products may not be economically competitive with lime/limestone FGD systems. The important factors influencing relative cost in declining order of importance are: (1) actual sludge disposal costs, (2) ultimate sulfur/acid market, and (3) scrubbing process costs. Superimposed on these uncertainties is the side variation in power plant conditions (retrofit difficulty, age, size, percent S in fuel, type and amount of land, local regulations, etc.).

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